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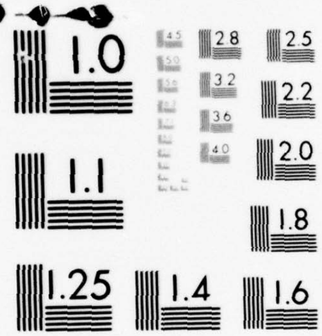
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AREA NAVIGATION/VERTICAL AREA NAVIGATION TERMINAL SIMULATION

William Crimbring

John Maurer

March 1977

FINAL REPORT

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16. Abstract

A dynamic simulation using the digital simulation facility at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey, was conducted to determine the effects on the air traffic control (ATC) system and the system users derivable from the use of area navigation (RNAV) and area navigation with vertical guidance (VNAV) in a high-density terminal area. The John F. Kennedy Airport airspace was configured with an RNAV/VNAV route system to provide the test bed for the study. The study analyzed selected controller workload and system performance measures for various mixtures of RNAV, VNAV, and radar-vectored operations. Results show that controllers can use RNAV/VNAV maneuvers in the control of traffic in lieu of radar vector techniques and that controller workload decreased as the level of RNAV/VNAV participation increased. Controller acceptance of RNAV/VNAV principles and techniques in the ATC terminal area increased as familiarity and experience with RNAV/VNAV were gained. Controllers favored the use of RNAV over a pure radar-vector environment, expressing the opinion that RNAV could provide benefits to both controller and system user. Significant decreases in controller communications workload and slight increases in operations were recorded as the percentages of RNAV/VNAV aircraft in the system were increased. In general, the orderliness of the ATC system improved as the percentage of RNAV/VNAV aircraft was increased. Input from two general aviation trainers (GAT's) was integrated with the targets from the digital simulation facility. The resultant data provide some insight into minimum avionics requirements for RNAV/VNAV equipment in the terminal area as well as professional pilot opinions concerning RNAV/VNAV ATC procedures, phraseologies, and techniques.

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PREFACE

The authors recognize that the successful completion of this activity would not have been possible without the sustained and dedicated efforts of many personnel of the Simulation and Analysis Division and the Aviation Facilities Division. In addition, they feel that several people deserve a special thanks for their outstanding contributions. They are: Mr. Francis M. Willett, Jr., Experimentation and Evaluation Branch, and Mrs. Iva Callio, Data Preparation Section, for their tireless efforts on the traffic samples and Link I data; Ms. Mary L. Cale, Mr. Richard D. Algeo, and Mr. Ralph G. Wilson, Jr., Systems Software Section, for their support of the software requirements throughout the conduct of these tests; and Messrs. Thomas E. Morgan, Jr., and Edward H. Stevens of the Computer Sciences Corporation, who, in addition to providing invaluable assistance in the test design and data reduction and analysis, created both the error model and the fuel consumption model used during this activity.

Finally, a most sincere thanks was earned by the air traffic control specialists, whose interest and dedication as test subjects were outstanding.

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INTRODUCTION

PURPOSE.

This report describes the second of several proposed dynamic simulation studies intended to assist in the orderly introduction of area navigation (RNAV) into the National Airspace System (NAS). The objective of this second simulation project was to determine the effects on the air traffic control (ATC) system and the system user of various percentages of RNAV, RNAV with vertical guidance (VNAV), and nonequipped aircraft.

BACKGROUND.

A Federal Aviation Administration (FAA)/Industry RNAV Task Force was formed to make a comprehensive study of the use of RNAV in the NAS. A request was submitted by Air Traffic Service, AAT-1, to the Systems Research and Development Service, ARD-1, to initiate research and development studies and simulation actions appropriate to the recommendations set forth in the RNAV Task Force report (reference 1). In response, ARD-1 has initiated a series of real-time simulations which would extend over a period of several years. The first of these simulations, completed in March 1974, was a conceptual study which investigated the impact of RNAV procedures and various mixes of RNAV equipped and radar-vectored traffic on the ATC system. The study also explored some of the possible system/user payoffs (reference 2). This report documents the second simulation, which compares the operational efficiency of RNAV, VNAV, and radar vectoring for the control of air traffic in the terminal area. In addition, the report discloses the impact of the introduction of various participation levels of VNAV-equipped aircraft into a mixed population of radar-vector/RNAV-equipped air traffic in a representative high-density terminal area. Participation level is defined as the percentage of RNAV- and/or VNAV-equipped aircraft present in the traffic sample. Finally, the utility of such innovative ATC concepts as vertically layered or "stacked" routes is evaluated.

Data collection for this activity began on August 18, 1975, and was completed on November 20, 1975. During this period, approximately 20,000 aircraft flights were simulated.

OBJECTIVES.

The general purpose of all RNAV/VNAV simulations is to assist in the orderly introduction of RNAV/VNAV into the NAS. The specific objectives of this simulation were;

a. To compare the ATC system performance while using radar vectors, RNAV, or VNAV procedures for the control of arrival and departure traffic in a representative high-density terminal area.

b. To evaluate the impact of various participation levels of RNAV, VNAV, and radar-vectored traffic on the ATC system performance.

c. To evaluate the impact of various participation levels of RNAV, VNAV, and radar-vectored traffic on the efficiency of operation of the system user.

d. To explore the effectiveness of vertically layered ("stacked") arrival routes.

e. To gather and appraise controller and pilot opinion concerning ATC procedures, phraseologies, terminal route design concepts, and workload relevant to the introduction of RNAV and/or VNAV into a busy terminal ATC system.

DISCUSSION

GLOSSARY.

The information concerning RNAV/VNAV terminology and navigational maneuvers was developed from the Software Requirements for RNAV/VNAV Terminal Simulation Memorandum (reference 3). The following definitions are provided in order to promote a common understanding of the terminology contained in this report:

AREA NAVIGATION (RNAV). A method of navigation that permits aircraft operations on any desired course within the coverage of station-referenced navigation signals or within the limits of self-contained system capability.

WAYPOINT (W/P). A predetermined geographical position, used for route or instrument approach definition or flight progress reporting purposes, that is defined relative to a combined VOR and TACAN system (VORTAC) station (i.e., bearing and distance). The latitude and longitude (L/L) of the W/P may be used in lieu of bearing and distance from the Navigation Aid (NAVAID). Two sequentially related W/P's define a route segment.

RNAV ROUTE. An enroute, arrival, or departure route, including Standard Instrument Departures (SID's) and Standard Terminal Arrival Routes (STAR's), consisting of consecutively linked route segments between W/P's.

PARALLEL OFFSET. An uncharted route which is parallel to an established (charted) route.

NEXT-LEG OFFSET. A specified parallel offset on the next leg (route segment) of the RNAV route.

DELAY FAN. A technique using RNAV to effect a delaying maneuver in lieu of radar vectoring.

VERTICAL NAVIGATION (VNAV). A capability which permits an RNAV-equipped aircraft to fly precise climb and descent paths without reference to ground-based glide/climb slopes.

ALONG-TRACK (VERTICAL) OFFSET. A capability to program the VNAV slope such that the desired altitude will be reached at a specified distance prior to, or beyond, the W/P.

FUNCTIONS.

Capability for the following control functions was provided for use in this simulation:

PARALLEL OFFSET (PRESENT POSITION). To effect a parallel offset from an aircraft's present position, the controller issued an offset distance and direction (left/right) instruction to the aircraft. He could also issue a turn or heading instruction to reach the specified offset. If no turn instruction was given, a standard angle of 45° was used by the aircraft to reach the specified offset distance (figure 1).

When instructed to fly an offset of this type, the aircraft would maintain the specified offset over subsequent legs unless instructed otherwise. The required geometry for turning from one leg to the next will be covered under OFFSET GEOMETRY IN TURNS. Standard control instructions, such as radar vectors, approach clearances, etc., would cancel the offset.

If a controller elected to modify an offset on a present leg, he could do so by the same method as for an initial offset, discussed above. The new offset would be applied to subsequent legs unless further modified.

NEXT-LEG PARALLEL OFFSET. For this function, the aircraft would continue on its present navigational course (or last assigned heading) to intercept the specified offset. Next-leg offset could be applied as discussed in the paragraph on parallel offsets, or could be specified by the controller in one of several ways. The various geometries associated with the next-leg offset are depicted in figure 2, and the methods of specifying each are given in the section describing phraseology.

OFFSET GEOMETRY IN TURNS. Various geometries were under consideration regarding navigation during turns where offsets were involved. For the purpose of the Digital Simulation Facility (DSF) simulation, the method adopted was a straightforward approach analogous to the present "radial-in/radial-out" method, except that in the RNAV case, the intersection between two legs was computed from the combined offset data, as illustrated in figure 2. If an aircraft's next leg was the final approach course, and the offset for this leg had been cancelled (i.e., by an approach clearance instruction, etc.), then "lock-on" to the final approach was accomplished in the same manner as is currently done.

DELAY FAN. The method for effecting this delay maneuver was, at the time, under study. Therefore, until resolved, the DSF was programmed for the delay fan maneuver to be performed in two ways, depending upon the foll[illegible] controller clearance:

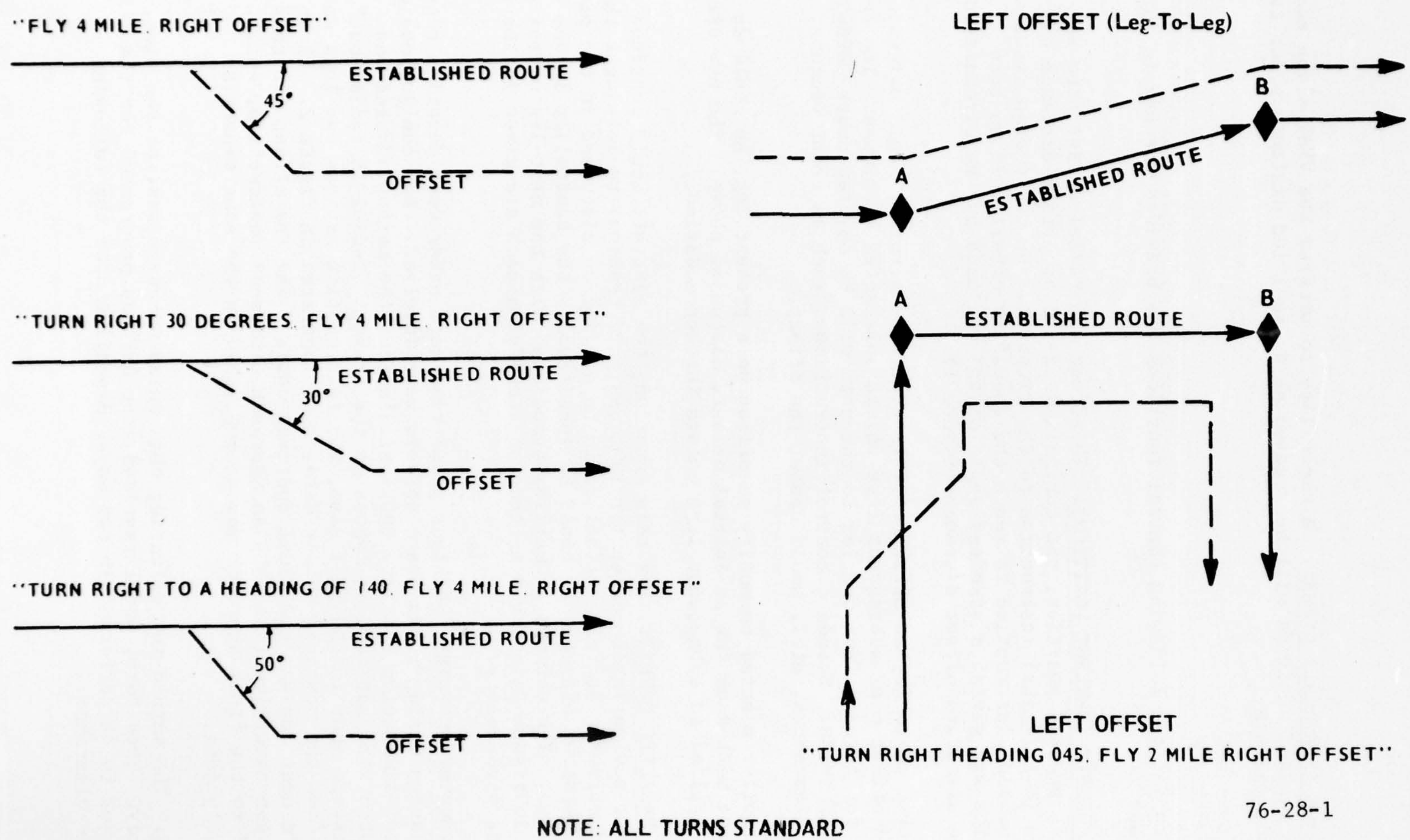
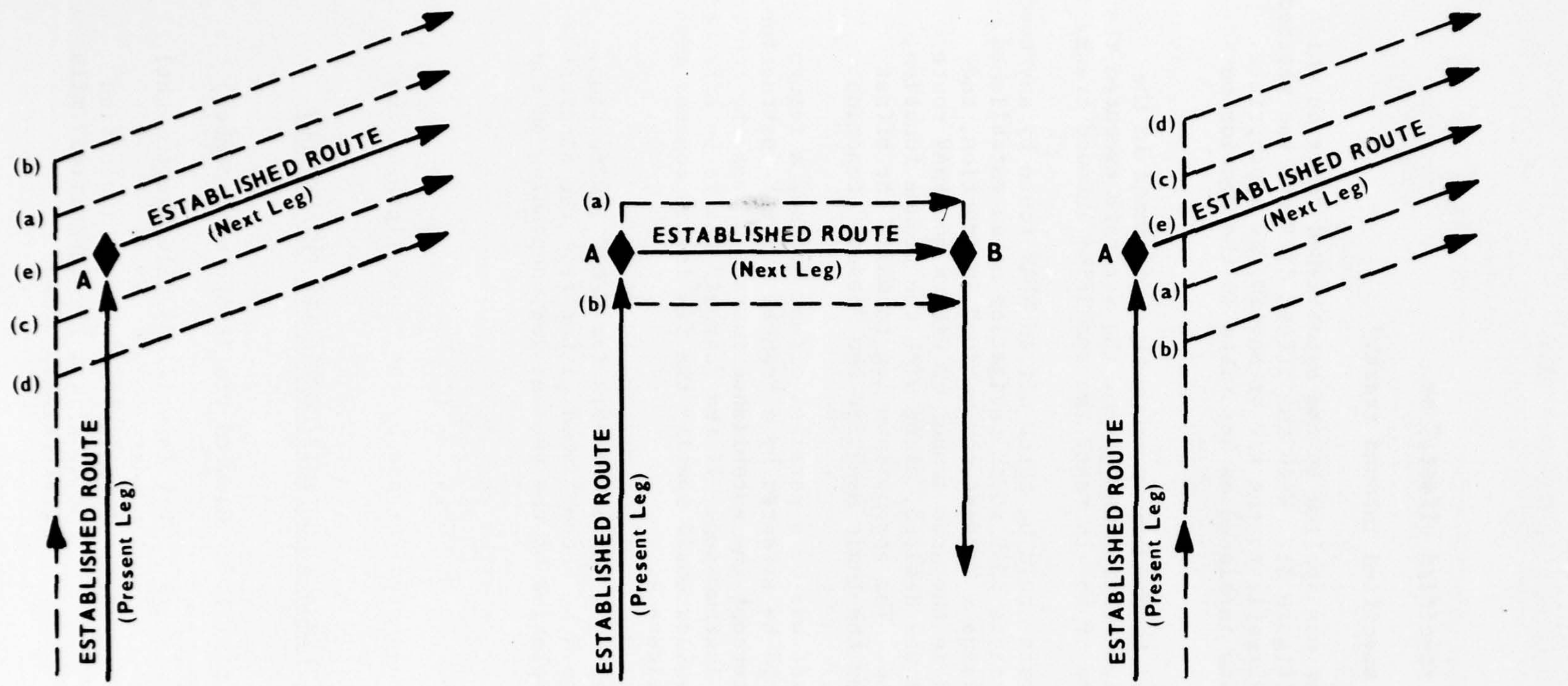


FIGURE 1. ESTABLISHMENT OF PARALLEL OFFSET AND OFFSET NAVIGATION



Before "A", aircraft is on left offset
After "A", offset is:
- (a) Same
- (b) Same direction; different distance
- (c) Different direction; same distance
- (d) Different direction; different distance
- (e) Cancelled

Before "A", aircraft is on established route
After "A", offset is:
- (a) Left to "B", then cancelled
- (b) Right to "B", then cancelled

Before "A", aircraft is on right offset
After "A" offset is:
- (a) Same
- (b) Same direction; different distance
- (c) Different direction; same distance
- (d) Different direction; different distance
- (e) Cancelled

NOTE: ALL TURNS STANDARD

FIGURE 2. NEXT-LEG OFFSET GEOMETRY

1. "To W/P (or NAVAID) via specified offset," or

2. "To W/P (or NAVAID) via specified inbound track."

In the first method, an offset was applied to the established route on which the aircraft was navigating (figure 3). When the offset distance was reached, the aircraft then proceeded directly to the W/P or NAVAID, as appropriate. The turn towards the offset was initiated as described in the section on parallel offsets.

The second method was executed in the manner currently programmed in the DSF, except that if no turn instruction was given, the aircraft executed the appropriate left or right turn of 45° to reach the specified inbound track.

RESUME NAVIGATION. The aircraft could be taken off an RNAV route by any heading or turn instruction. To reinstate RNAV route navigation on an established route, the controller would issue a "resume navigation" instruction, and the function was accomplished in the same manner as with a non-RNAV route. However, if a parallel offset was desired, along with the resume function, an offset message was required. The appropriate leg to which the offset applied could be determined by the logic used for the "resume" function.

CANCEL OFFSET. If the aircraft was on a parallel offset course, a return to the established course could be effected by a "cancel offset" instruction. A turn of 45° was made to intercept the established course, unless the controller issued a turn or heading instruction. If the "cancel" was to be effected at a W/P or NAVAID, the controller would specify the fix in his control message. These cases are depicted in figure 4.

Offset could also be cancelled by a "direct-to-fix (or W/P)" instruction. This direct-to-fix routing could be accomplished either from the aircraft's present position or after completion of the present leg, depending on the control instruction.

PHRASEOLOGY.

The following messages were suggested for use by the controllers during this simulation:

FUNCTION		MESSAGE CONTENTS/CONTROLLER PHRASEOLOGY
Flight via Established RNAV Routes	1.	Cleared via (Route name/number)
Parallel Offset From Present Position (figure 1)	1.	Fly (specified) mile (left/right) offset
	2.	Turn (left/right) to (specified heading) and fly (specified) mile (left/right) offset.

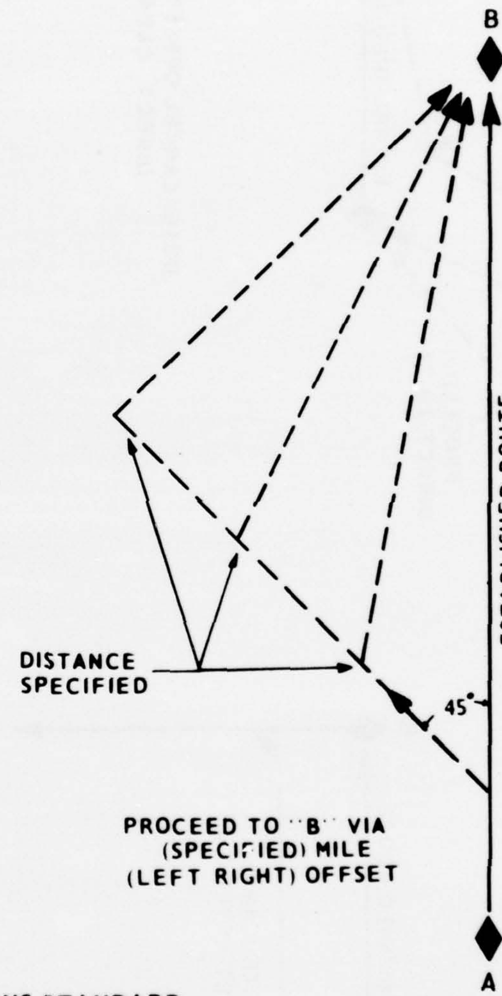
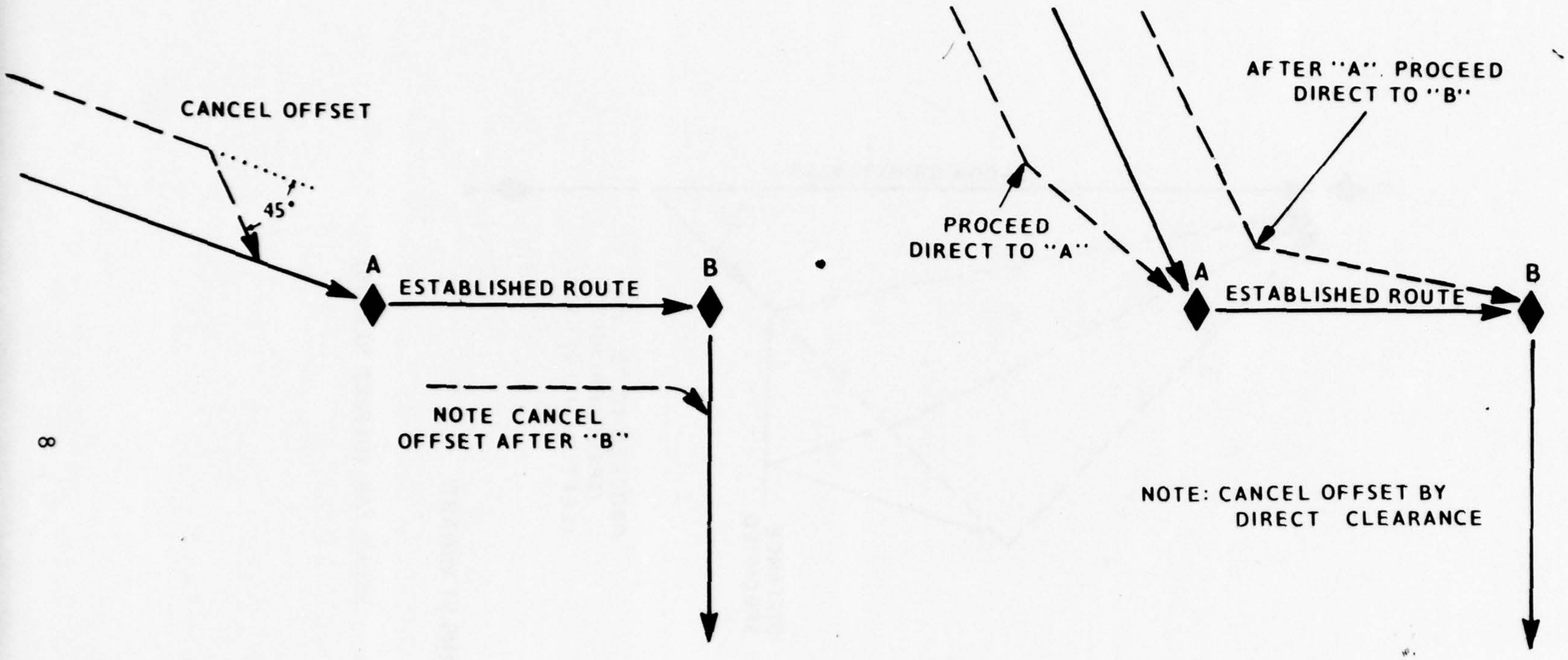


FIGURE 3. DELAY FAN (OFFSET METHOD)



NOTE: ALL TURNS STANDARD

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FIGURE 4. CANCEL OFFSET METHODOLOGY

	3.	Turn (specified) degrees (left/right) and fly (specified) mile offset.
Next-Leg Offset (figure 2)	1.	After (specified) fix fly (specified) mile (left/right) offset.
Cancel Offset (figure 4)	1.	Cancel offset.
	2.	After (specified) fix, cancel offset.
	3.	Proceed direct to (specified) fix.
	4.	After (specified) fix, proceed direct to (specified) fix.
Resume Navigation	1.	(Position) Resume navigation.
	2.	(Position) Resume navigation with (specified) mile (left/right) offset.
Delay Fan (figure 3)	1.	Proceed to (specified) waypoint via (specified) mile (left/right) offset.
	2.	Turn (left/right) to (specified) heading proceed to (specified) waypoint via (specified) mile offset.
	3.	Turn (left/right) to (specified) heading, proceed to (specified) waypoint via (specified) inbound track.
Vertical Navigation Routing	1.	Cleared via (specified) VNAV route.
VNAV Crossing Instructions	1.	Cross (specified) waypoint at (specified) altitude.
Along-Track (Vertical) Offset	1.	Climb/descend so as to reach (specified) altitude (specified) distance (before/after) (specified) waypoint.
Resume Normal Climb/Descent	1.	Resume normal climb/descent after (specified) waypoint.

METHOD OF APPROACH

GENERAL.

The use of RNAV and VNAV control techniques for the management of arrival and departure traffic in a high-density terminal area was tested by a real-time dynamic simulation of the John F. Kennedy (JFK) portion of the New York Terminal Area airspace. Comparisons of several participation levels of RNAV, VNAV, and radar-vectored traffic were made over a route structure which was designed for a total RNAV environment.

Two general aviation trainer (GAT) flight simulators were interfaced with NAFEC's DSF. (For a complete description of the DSF, see "Digital Simulation Facility Users' Guide", reference 4.) The GAT's were equipped with actual RNAV and VNAV computers and were operated by trained instrument-rated pilots. They provided additional aircraft targets for the real-time simulation as well as an element of realism and a means for pilot input concerning control procedures, phraseologies, RNAV/VNAV route structures and some objective data concerning the minimum operational characteristics required for use in the terminal ATC system. The two GAT's and their computers comprise the GAT II Facility.

The GAT IIA is representative of a general aviation, light, twin-engine aircraft. It was equipped with conventional instruments, dual navigation/communication (NAV/COM), course deviation indicator (CDI), and a King-KNC-610 RNAV computer (figure 5). The KNC-610 is a single-waypoint RNAV computer. It is a station-oriented system which effectively moves the VORTAC to a phantom location called a "waypoint." The desired course to the waypoint is then set with the omni bearing selector (OBS) control on the pilot's CDI as it is done in conventional VOR navigation. A corresponding course error signal is then shown on the CDI. The magnitude of the deviation is shown in nautical miles (nmi) rather than degrees as is the case with VOR systems. This is referred to as the course width.

Two area navigation modes of operation are available to the KNC-610. They are designated RNAV and Approach (APPR) for use in enroute and terminal areas, respectively. The aircraft navigation displays function the same in either mode, except that the course width is ± 4 nmi (7.408 kilometers (km)) in the RNAV mode and ± 1 1/4 nmi (0.463 km) in the APPR mode. Data entry is manual.

The GAT IIB is representative of a general aviation, heavy, twin-engine aircraft and was equipped with conventional instruments, plus a flight director, and an EDO/Thompson-CSF 3D RNAV System (TCE-71A) (figure 6). The TCE-71A is a 20-waypoint, fully automatic RNAV/VNAV system. VOR stations may be tuned manually or automatically, as required. Offsets from 1 nmi (1.852 km) to 20 nmi (37.04 km) left or right of track may be flown.

The VNAV portion of the TCE-71A permits programmed climbs and descents either to or from waypoints. It can be operated to fly a selected flightpath angle or it can automatically compute its own flightpath angle by utilizing the altitude which has been stored with the next waypoint.

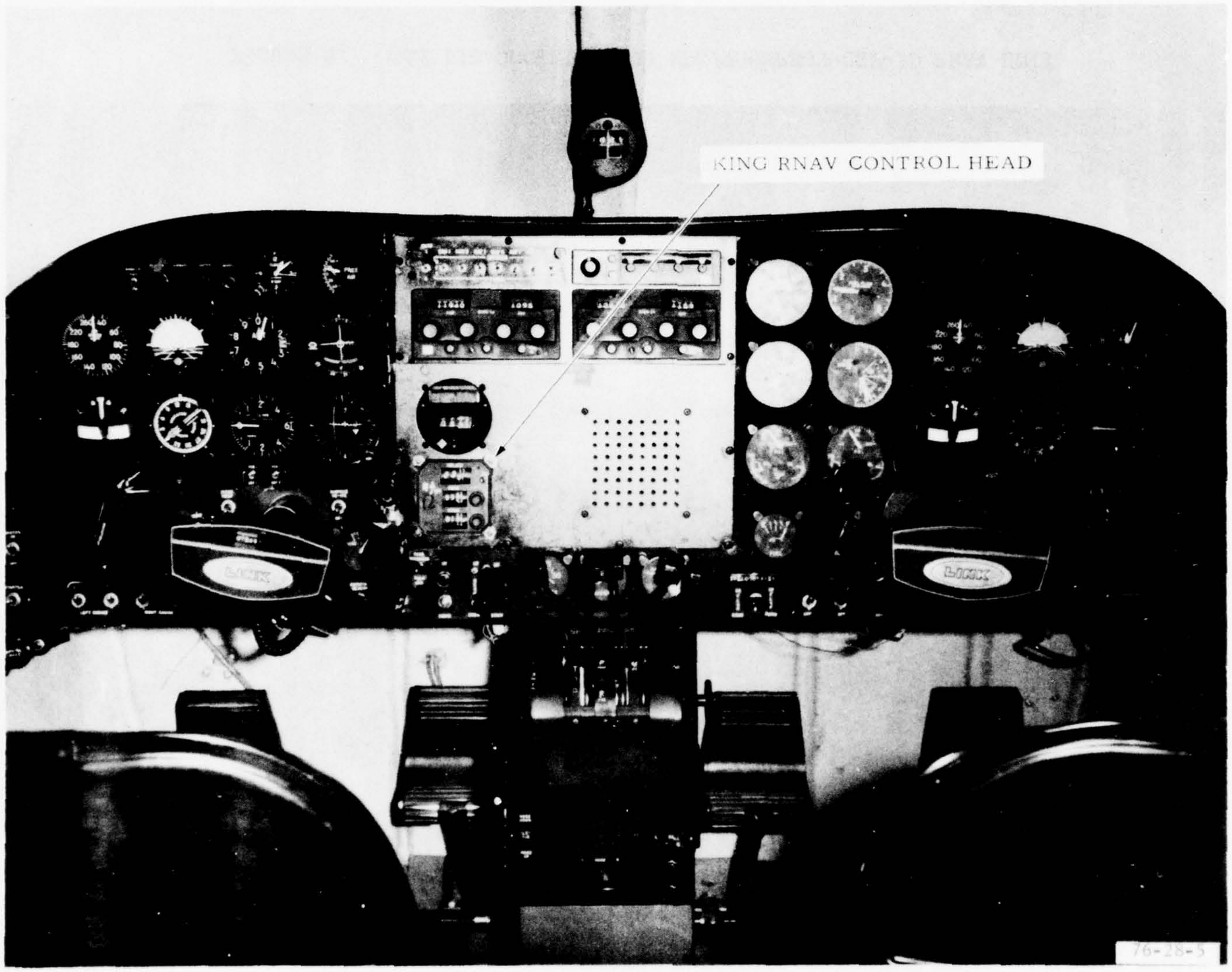


FIGURE 5. GAT IIA COCKPIT WITH KING-KNC-610 RNAV UNIT

FIGURE 6. GAT IIB COCKPIT WITH EDO/THOMPSON-CSF-3D RNAV UNIT

Each GAT was scheduled to fly one arrival and one departure during each data collection period, except that the GAT IIA was, of necessity, excluded from all runs requiring total VNAV participation. The GAT II Facility was interfaced with the DSF as shown in figure 7.

The DSF target generator caused the targets to fly in accordance with flight plan inputs. The GAT II simulators were flown by instrument-rated pilots along predetermined flight plan routes. Controllers were able to modify the paths of aircraft under their control through a voice link with the DSF and the GAT II pilots. Keyboard entries by the DSF pilots and the use of the standard aircraft controls by the GAT II pilots provided the necessary responses to control instructions. Errors were applied to the flightpaths of all targets according to the parameters discussed later under ERROR MODELS.

Controlled aircraft targets (all JFK arrivals and departures) were handled by 19 DSF "pilot" positions. Four other "pilots" handled traffic in and out of LaGuardia, Newark, and the satellite airports. These aircraft were uncontrolled in that they started, flew, and terminated automatically. Their purpose was to provide aircraft target activity on the controller displays at locations where the two other airports' traffic would normally interact with JFK.

The air traffic controllers operated in the DSF control room, which was configured as an ARTS III facility. Seven radar displays were used to accommodate the seven control positions, as depicted in figure 8. All of the controller positions, except the one designated as the "JFK Tower," were data positions. The Tower position was responsible for starting all departures and monitoring the approach and landing of all arrivals. This position also provided the initial handling of missed approaches.

The number of control positions simulated differed from the present-day JFK staffing of three feeders, one intermediate, and one final controller. the intermediate position was changed to a feeder position when the number of arrival routes was increased from three to four. The second final approach position was added when the new parallel runway 22 was made a part of the simulated geography. During the exploratory period, it was found that the reorganization of the traffic flows, coupled with the addition of another final controller, allowed the four feeder positions to be combined into the two which were finally simulated.

SIMULATION PROCEDURES.

In order to have the simulated targets exhibit more realistic flight patterns, the Computer Sciences Corporation (CSC) developed an error model along the lines set forth by McConkey and Moleji (references 5 and 6) incorporating typical navigation system errors into the DSF. A more detailed description can be found in their document (reference 7) and appendix A of this report.

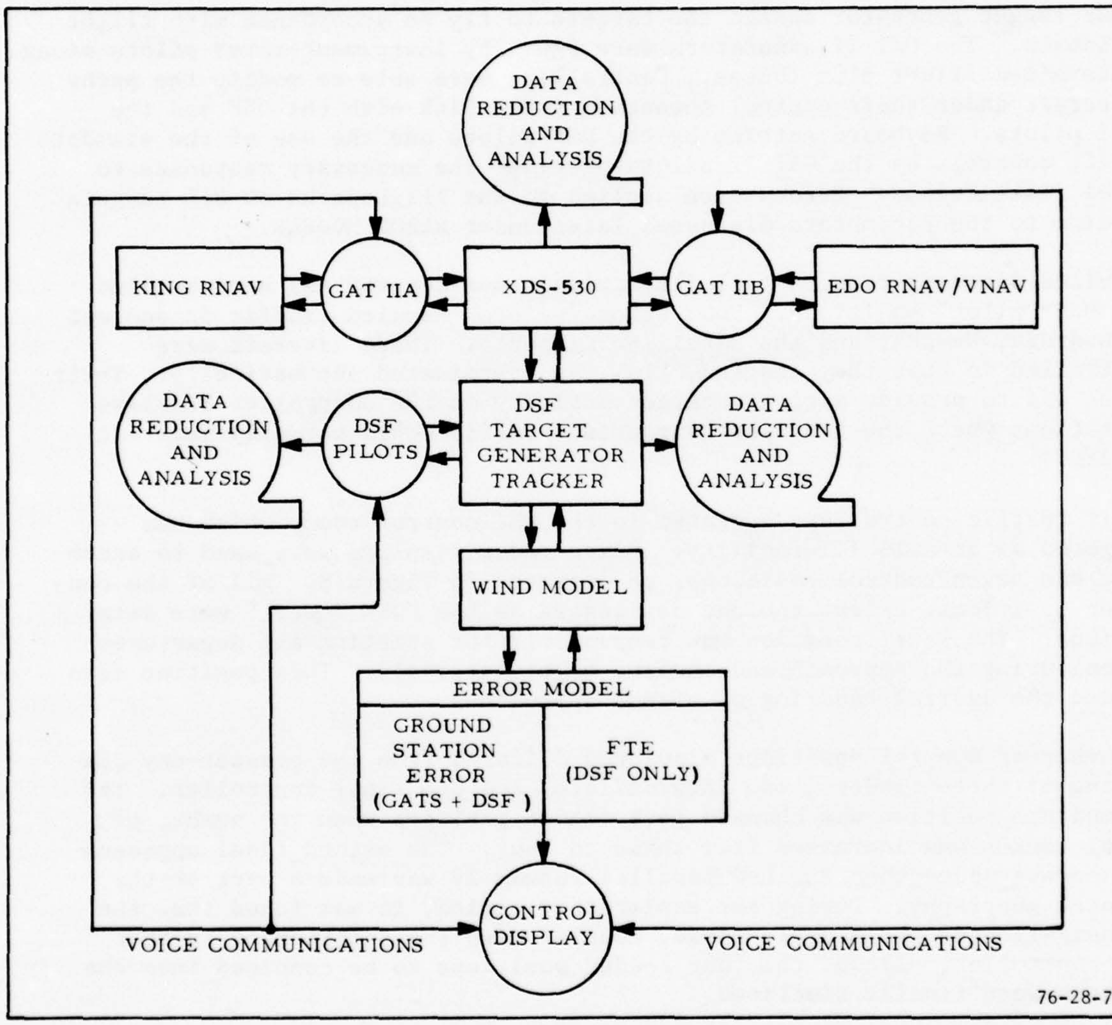


FIGURE 7. GAT II--DSF INTERFACE

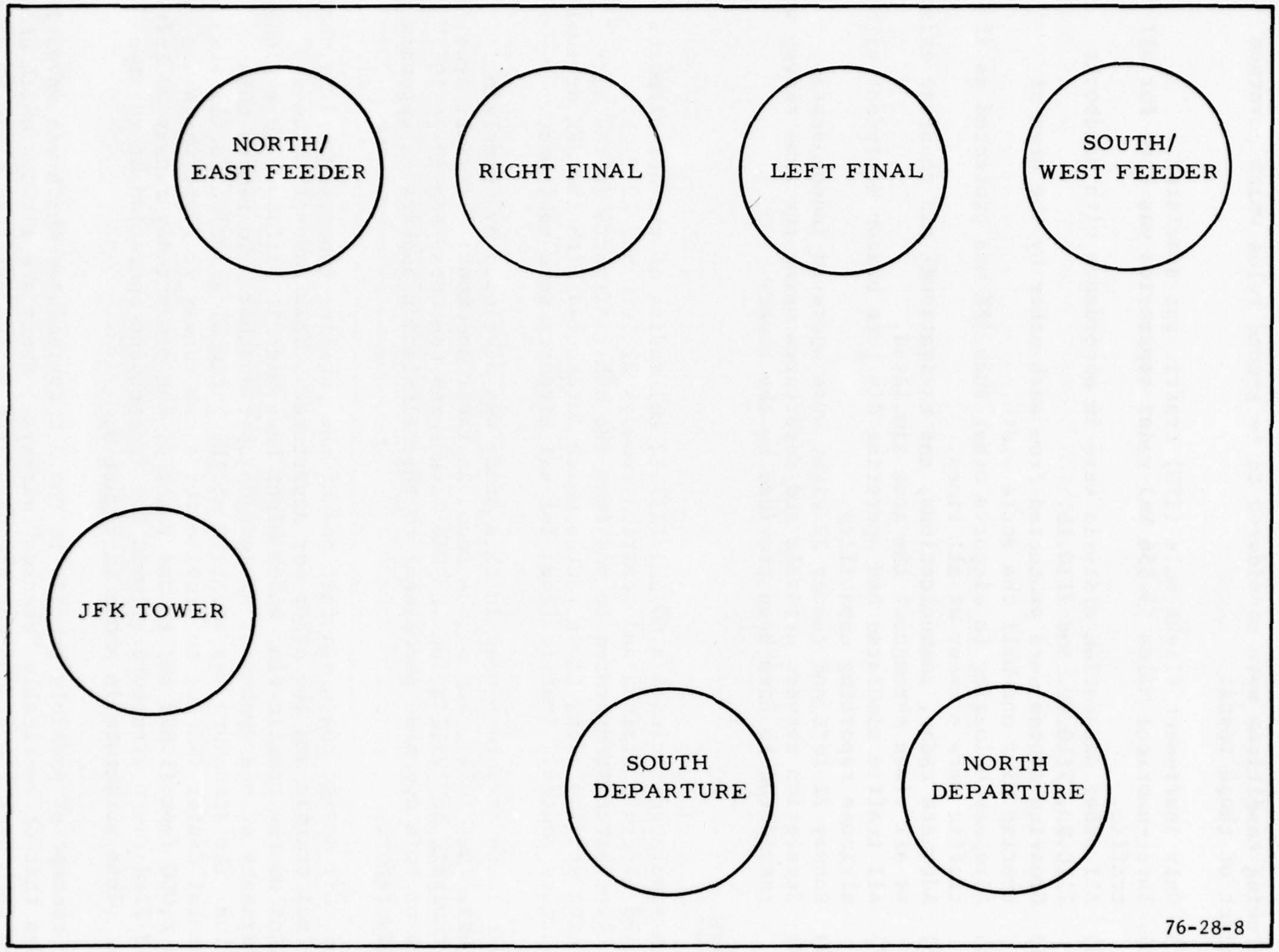


FIGURE 8. CONTROLLER LABORATORY CONFIGURATION

TEST DESIGN GROUND RULES.

The following conditions were considered to be ground rules which governed the conduct of these tests:

(1) Only instrument flight rule (IFR) traffic was simulated.
(2) Three-nautical miles (5.556 km) radar separation was used for all traffic.
(3) All other separation criteria were in accordance with Handbooks 7110.8D, 7110.9D, and 7110.18.
(4) Crossing routes were protected from each other by the area of overlap plus one-half the route width.
(5) Airspace belonging to airports other than JFK was protected as if traffic were present at all times.
(6) Adequate radar, communications, and navigational aid coverage existed at all times throughout the area simulated.
(7) All traffic simulated had operating discrete beacon equipment with altitude reporting capability.
(8) Runway 22 left and runway 22 right were operated independently.
(9) Separation between arrivals and departures using the same runway was considered to have been provided by the tower.

GEOGRAPHY.

The area simulated included a 60 nmi (111.12 km) radius of the JFK airport. Controlled aircraft arrived and departed runways 22 left and 22 right. Uncontrolled aircraft operated to and from the other airports in the airspace being studied along those routes which interacted with the JFK arrival and departure routes. Traffic flows for all airports were southwest.

The basic route structure used in this study was developed by Champlain Technology, Inc. (CTI), and may be found in their document: "Terminal Area Design Analysis and Validation of RNAV Task Force Concepts, FAA-RD-76-194." The part of this document pertainent to this simulation appears as appendix B of this report.

The basic CTI design conceived that one of the parallel runways would be used for arrival traffic and the other for departures. This concept imposed a constraint on the traffic flow which might have made it difficult to evaluate the efficiency of one system of navigation over another. To remove this limitation, the structure was modified at the National Aviation Facilities Experimental Center (NAFEC) to provide for a new runway 22 right which was located 6,000 feet (1.829 km) to the right of the present-day runway 22 left. This modified route structure allowed for independent operation of the two runways. This structure is shown in figure 9.

Another concept of possible benefit to the ATC system/user which was investigated was that of vertically "stacked" airways. These are airways which utilize the same path over the ground but are separated in the vertical plane by different altitudes or slopes. One possible transition from a "stacked" route would be via a horizontal offset with a transition to an instrument landing system (ILS) (figure 10).

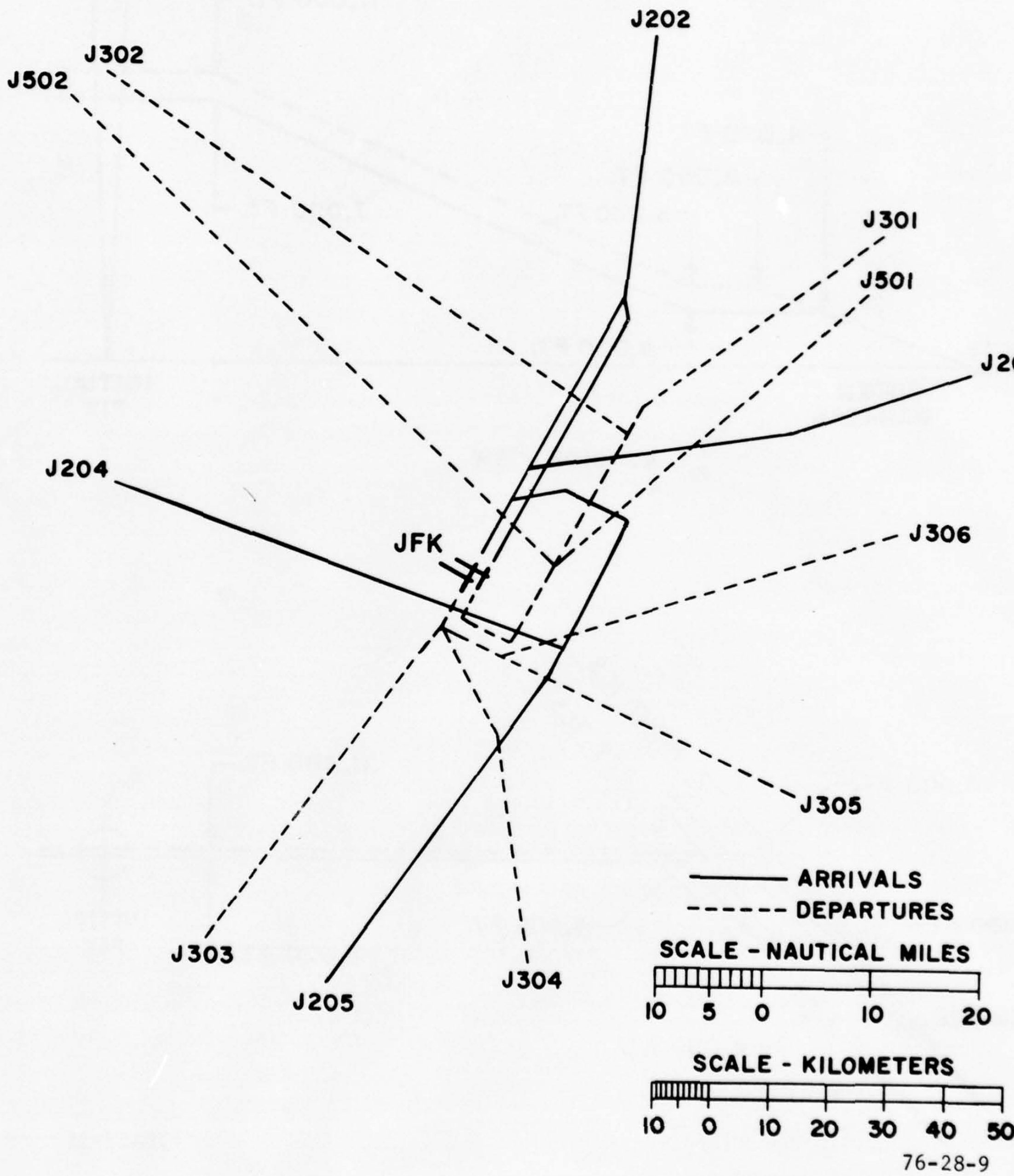


FIGURE 9. NAFEC-MODIFIED JFK ROUTE STRUCTURE

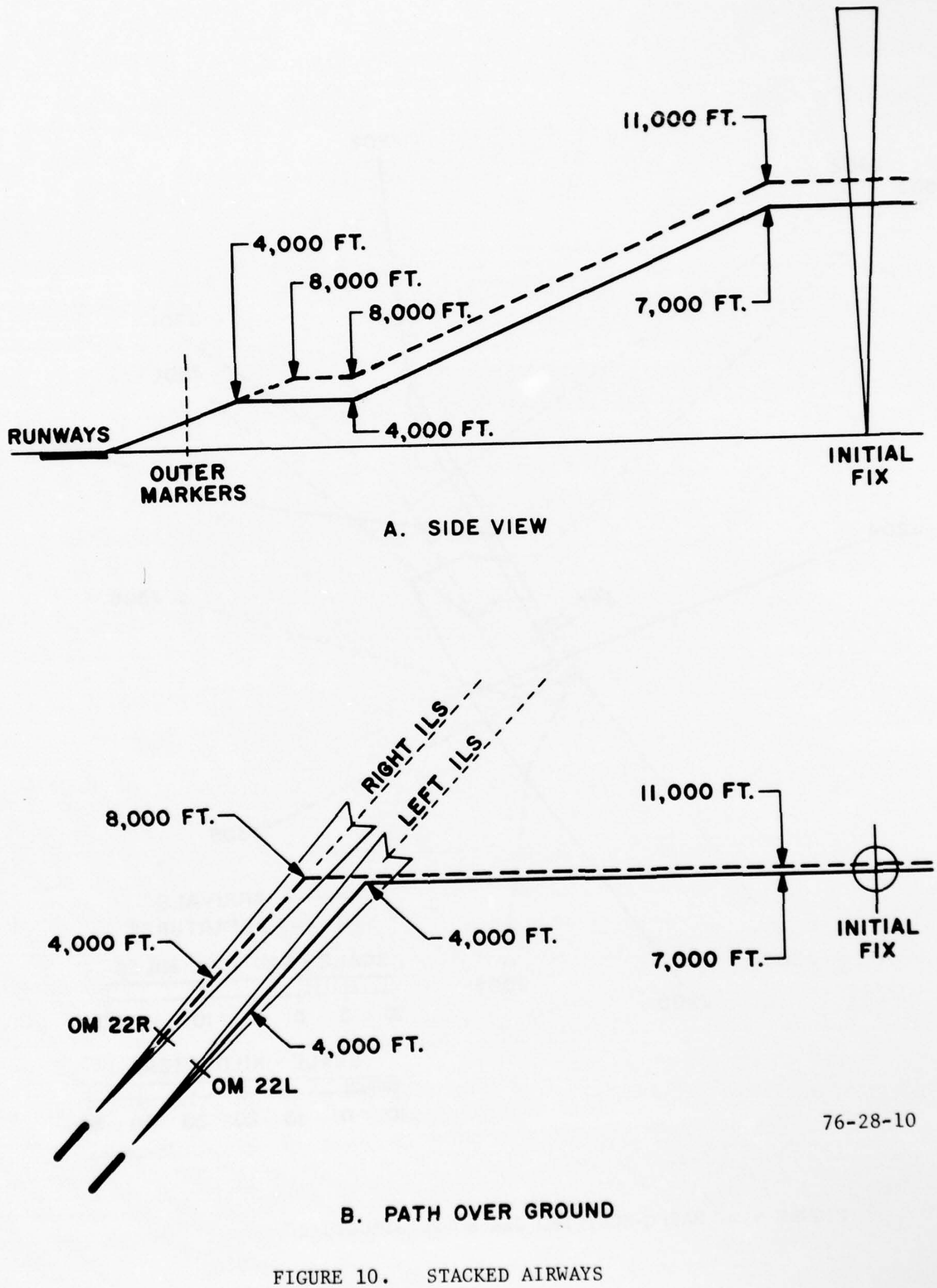


FIGURE 10. STACKED AIRWAYS

WIND MODEL.

There was a wind model available for use by the DSF. In this RNAV/VNAV experiment, it was applied as follows: the wind at the surface was constant as to direction and velocity. The velocity increased at a constant rate as a function of altitude above the surface. Likewise, the direction changed in a clockwise rotation as altitude increased. The wind pattern was established by setting direction and velocity values for three levels: surface, 225° at 15 knots (27.78 km/h); 5,000 feet (1,524 meters (m)), 250° at 25 knots (46.3 km/h); and 20,000 feet (6,096 m), 300° at 40 knots (74.08 km/h). Values for altitudes between these levels were determined by the computer program on a pro rata basis. Once established, the wind pattern was not varied throughout the simulation.

DATA BLOCKS.

The data block information was presented on the radar displays in the standard ARTS III format, except that the letters "R" or "V" were displayed in the space between the mode C altitude and the groundspeed to indicate when a target was RNAV or VNAV equipped. These equipment qualifier letters blinked whenever an aircraft was taken off of its RNAV or VNAV route. The blinking stopped as soon as a control instruction was issued which allowed the aircraft to resume its navigation using either its RNAV or VNAV computer. For VNAV aircraft whose vertical profile was disturbed, the mode C altitude was blinked. When a control instruction was issued which allowed the aircraft to resume navigation using the vertical guidance from its VNAV computer, the blinking ceased.

The concept of using letters in the data blocks to identify RNAV/VNAV-equipped aircraft was carried over from the first RNAV terminal simulation where it was found to be useful. In this simulation, the blinking function was program controlled by DSF pilots' keyboard entries. In an operational facility, the function would have to be programmed into the ARTS for manual entry by the controllers.

TEST MATRIX.

This simulation investigated two major areas of impact of RNAV/VNAV on the ATC system/user. The first compared the relative effectiveness of three "pure" ATC systems, radar-vectoring, RNAV, and VNAV. The second examined the effect of various participation levels of radar-vectored, RNAV, and VNAV traffic on the ATC system/user. Although the purpose of each phase was somewhat different, they were tested concurrently in order that no benefit of training on one phase would accrue to the other.

Two levels of RNAV and VNAV equipment capabilities were simulated in this experiment (table 1). The higher level was similar in capability to the type of equipment which would be used by the airlines, while the lower level was similar to the less expensive is expected to be used by general aviation. The RNAV and VNAV equipment installed in the two GAT's was representative of the latter. A constant ratio of four to one in favor of the higher capability level was employed throughout the simulation.

TABLE 1. RNAV/VNAV CAPABILITIES

Capability	RNAV High	RNAV Low	VNAV High	VNAV Low
Parallel Offset	Yes	Yes	Yes	Yes
a. Granularity	1 nmi (1.852 km)	1 nmi (1.852 km)	1 nmi (1.852 km)	1 nmi (1.852 km)
b. Maximum distance	20 nmi (37.04 km)	4 nmi (7.408 km)	20 nmi (37.04 km)	4 nmi (7.408 km)
Along-Track (Vertical) Offset	N/A	N/A	Yes	No
Direct to Waypoint	Yes	Yes	Yes	Yes
Delay Fan	Yes	Yes	Yes	Yes
Turn Anticipation	Yes	No	Yes	No
Slant Range Correction	Yes	No	Yes	No

TABLE 2. NUMBER OF TEST RUNS BY VARIABLES

	Percentage of VNAV Traffic				
	0	25	50	75	100
100	4				
75	4	4			
50	4	4	4		
25	4	4	4	4	
0	4	4	4	4	4

Note: The balance of traffic in each cell needed to bring the total to 100 percent is radar-vectored traffic.

Four controller teams were utilized. Each team completed all of the 15 conditions, as shown in table 2, before the next team began their series. Using this approach, it was possible to test for differences between equipment capabilities (thus making comparisons and testing for significant advantages and/or disadvantages), route structure, and interaction between route structure and equipment catagories while removing the variations caused by the controller teams.

TRAFFIC SAMPLE.

One basic traffic sample was employed throughout the simulation. It was varied according to the participation levels of RNAV and/or VNAV equipment specified for each test cell. Whenever RNAV and/or VNAV equipment was present in the sample, 80 percent was high capability, 20 percent low capability.

Traffic was evenly distributed over each arrival and departure route so that the ratio of aircraft types and equipment was the same for each route as it was for the entire facility. The amount of traffic available was in excess of the system's capacity.

TRAINING.

Additional procedures and phraseologies relative to the control of RNAV/VNAV aircraft were developed during the training and exploratory phases of this experiment. The controllers were instructed to provide air traffic control and related services to all aircraft under their jurisdiction. Detailed arrival and departure procedures were defined in controller handouts which were distributed prior to the begining of the laboratory training.

The DSF pilots were trained during the same period as the controllers. The instrument-rated pilots who operated the GAT II cockpit simulators received their training near the end of the exploratory phase. Both DSF and GAT pilots were instructed to operate their aircraft in accordance with their assigned flight plans and any modifications to these flight plans issued by the controllers during their flight.

Throughout the weeks of classroom and laboratory training and the exploratory phase of the experiment, pilot and controller opinions were actively sought concerning routes, procedures, phraseologies, and tactics. Such suggestions which would improve the operations were incorporated into the test design.

EXPLORATORY PHASE.

At the conclusion of the controller/pilot training period, a series of exploratory runs were conducted. At this time, the following two major areas were investigated:

1. Any possible benefit which would be unique to the use of VNAV, including the utility of "stacked airways," and

2. Validation of the terminal route structure created by CTI and modified by the project team.

During the training and exploratory phases, the controllers were encouraged to envision any unique way which VNAV could be utilized to provide some operational advantage not inherent in RNAV without vertical guidance. No constraints were placed on their efforts to develop a "pure VNAV" route structure which could be of benefit to the ATC system or user. As a result of their investigations, there was found no need for, or any advantage to, any unique or discrete VNAV routes to be included in the route structure for dynamic simulation. No use could be found for "stacked" routes due to problems of entry or exit from "stacked" routes.

The controllers felt that the proposed route structure was adequate for this simulation with one exception. They requested that the airspace to the east of the JFK Airport be restructured to allow the departures to operate outside of the downwind leg which they felt should be moved closer to the airport. The new design (figure 11) was verified by further exploratory runs and was the structure used during data collection. This particular design was preferred by the controllers, since it provided more flexibility to modify arrival and departure flightpaths without adverse effect on the system user.

DATA COLLECTION.

A history of each flight was recorded on magnetic tape. This history was analyzed to provide measurements of system performance and controller workload. In addition, the controllers and pilots were debriefed and interviewed, which provided a quantity of subjective data and recommendations regarding the use of RNAV/VNAV. The five controllers from various ATC field facilities, who had not been exposed to RNAV/VNAV, were administered questionnaires designed to measure their reaction to the introduction and use of RNAV/VNAV in the ATC system.

Instead of the usual finite data period, the start and end of the data collection for each test were triggered by the entry of the first of a series of discrete (key) flights and the completion of the last one. This group of key data flights consisted of 64 arrivals and 80 departures which were quantitatively balanced by type, RNAV/VNAV equipment, and performance characteristics over the various routes. These key flights provided a stable data base for some of the system performance measures.

The measurements recorded and analyzed are listed and defined as follows:

1. Controller Utilization of RNAV/VNAV Functions is a compilation of the number of times each RNAV/VNAV function was used throughout the simlation.

2. Number of Radio Contacts Per Control Position is a count of the number of controller-to-pilot radio transmissions made by each controller during each data collection period.

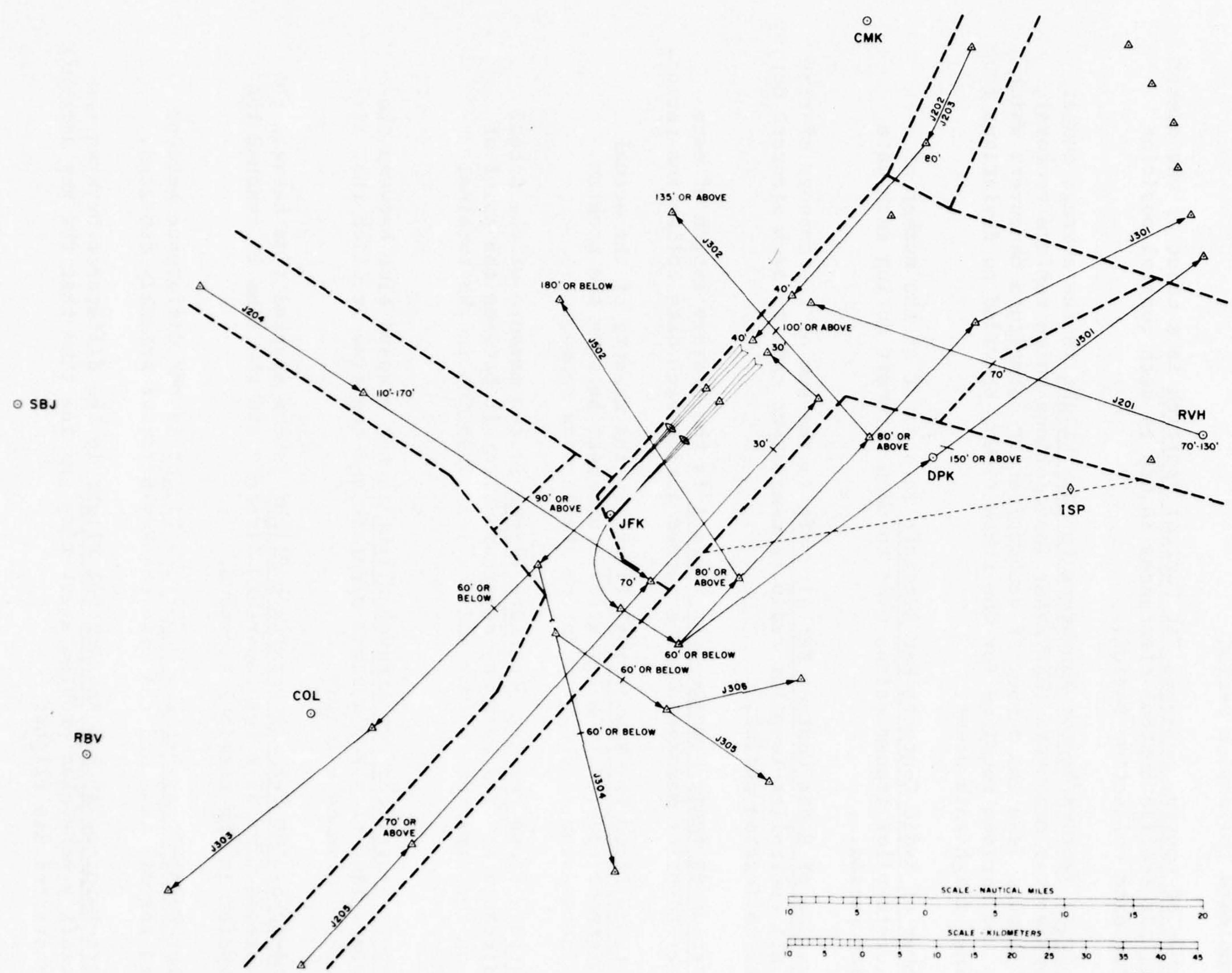


FIGURE 11. CONTROLLER-MODIFIED ROUTE STRUCTURE

3. Duration of Radio Contacts Per Control Position is the sum of the amounts of time used in each controller-to-pilot radio transmission by each controller during the data collection period.

4. Number of Control Messages Per Control Position is a count of the number of actual air traffic control clearances issued by each control position during the data collection period.

5. Residual Vectors/Vector Maneuvers Per Key Flight is the average number of vectors/vector maneuvers (RNAV/VNAV instructions which replace vectors), per key flight, less the number of vectors/vector substitute maneuvers which would be the minimum required for the route flown, provided no deviations from the nominal flightpath occur.

6. Number of Radio Contacts Per Aircraft is a count of the number of controller-to-pilot transmissions made to each aircraft during each data collection period.

7. Duration of Radio Contact Per Aircraft is the sum of the amounts of time used in all controller-to-pilot radio transmissions made to each aircraft during each data collection period.

8. Duration of Radio Messages Per Contact is the average length of each controller-to-pilot message which occurred during each data collection period.

9. Distance Flown Per Key Arrival Flight is the measure of the actual flight distance covered by a key arrival aircraft between the problem entry point and the touchdown point on the landing runway.

10. Distance Flown Per Key Departure Flight is the measure of the actual flight distance covered by a key departure aircraft between the point of takeoff on the departure runway and the last waypoint in the terminal airspace.

11. Time-in-System Per Key Arrival Flight is the elapsed time between the actual start time of a key arrival aircraft and the time at which that aircraft touched down on a runway.

12. Time-in-System Per Key Departure Flight is the elapsed time between the actual takeoff time of a key departure aircraft and the time it reached the last waypoint in the terminal airspace.

13. Start-Point-Delay Per Key Departure Flight is the difference between scheduled takeoff time and the time the key aircraft actually departed.

14. Start-Point-Delay Per Key Arrival Flight is the difference between the key aircraft's scheduled problem start time and the time that the key aircraft actually started its flight.

15. Hourly Arrival Operations Rate is the average number of aircraft which touched down each hour during each data collection period.

16. Hourly Departure Operations Rate is the average number of aircraft which took off each hour during each data collection period.

17. Hourly Operations Rate is the aggregate of the previous two measures.

18. Fuel Consumed is the amount of fuel estimated to have been used by each key flight.

19. RNAV Broken Reports is a measure of how many times a key RNAV/VNAV-equipped flight was taken out of RNAV/VNAV mode by use of radar vectors.

20. VNAV Broken Reports is a measure of how many times a key VNAV-equipped flight was taken off its computer-controlled vertical gradient.

METHODS OF ANALYSIS

The experimental design used was specified to (1) allow the most power (i.e., probability of detecting differences) in making inferences about the dynamic effects of the percentage of RNAV- and VNAV-equipped aircraft in the system, and (2) evaluate the interaction of various mixes of RNAV, VNAV, and radar-vectored traffic. The traffic was balanced over each of the arrival and departure sectors to allow comparisons by route, as well as by position.

Multiple regression techniques were used to estimate the statistical relationships between the design variables and the various performance measures. (A performance measure is a quantitative measurement of the system response during the data run.) The standard "F" test, Mood and Graybill (reference 8), was employed for determining whether the regressions were significant; that is, whether or not the percentage of RNAV or VNAV aircraft in the system affected the observed performance measures. The significance level, i.e., the alpha (α) level, is interpreted as the odds that the observed trends would be expected to be due to chance. For the performance measures which demonstrated statistically similar trends for both RNAV and VNAV, simple linear regression lines were fitted for the total percentage of RNAV/VNAV-equipped aircraft.

The residuals, i.e., the differences between the predicted values and the actual observed values, were plotted to validate regression equations. A linear regression model (i.e., a straight-line fit) accurately described the significant relationships between the performance measures and the percentage of RNAV/VNAV-equipped aircraft.

Four different arrangements of the test controllers in the simulated operating positions were used to replicate the experiment at each participation level. The controller teams added another source of variation to the results which, if not eliminated, would reduce the effect of the analysis. For this reason,

the data collected by the controllers were standardized to remove the additive controller team effects. A team's additive effect was taken to be the difference between average response over the five levels of RNAV/VNAV participation for that team and the overall average for all four teams. Under this procedure the average response remained constant, only the magnitude of variations around that average was reduced.

The data are presented either in the form of linear regression equations or averages, depending on whether or not there was a statistically significant relationship between the value of that measure and the percentage of RNAV or VNAV aircraft in the system. The regression equations are written in the form:

$$P = A + \beta R + CV$$

where

- P is the value of the measure,
- A is the intercept,
- β is the slope of the line with respect to the percentage, R, of RNAV aircraft, and
- C is the slope of the line with respect to the percentage, V, of VNAV aircraft.

If the percentage of VNAV did not affect the performance measure P, the coefficient A would be zero, and the equation would be reduced to;

$$P = A + \beta R$$

The intercept value represents the estimated level of P with no RNAV/VNAV-equipped aircraft in the system. The slope coefficients, B and C, were equal if the effects of RNAV and VNAV were the same. In this condition, the regression model used was;

$$P = A + \beta E$$

where;

β is the slope with respect to the total percentage, E, of RNAV/VNAV aircraft in the system; i.e., for a traffic density of 25-percent VNAV and 50-percent RNAV-equipped aircraft, then E would be 75 in the above equation. For specific cases, numeric values would replace A and β. For example, suppose A = 20.0 and β = 0.40, then the regression equation would be;

$$P = 20.0 + 0.40E$$

This relationship can be shown in pictorial form as in figure 12. In that figure, the value of A, in this case 20.0, is the value of P at which the line crosses the axis. The value of the slope, β, in this case 0.40, represents the rate at which the value of P changes for every unit increase of E. Specifically, for every percentage point that the level of RNAV/VNAV participation is increased, the value of P would increase 0.40 unit. In general, the value of the slope can be either positive or negative. For positive values, the line slopes upward from left to right as shown; for negative values, it would slope downward from left to right.

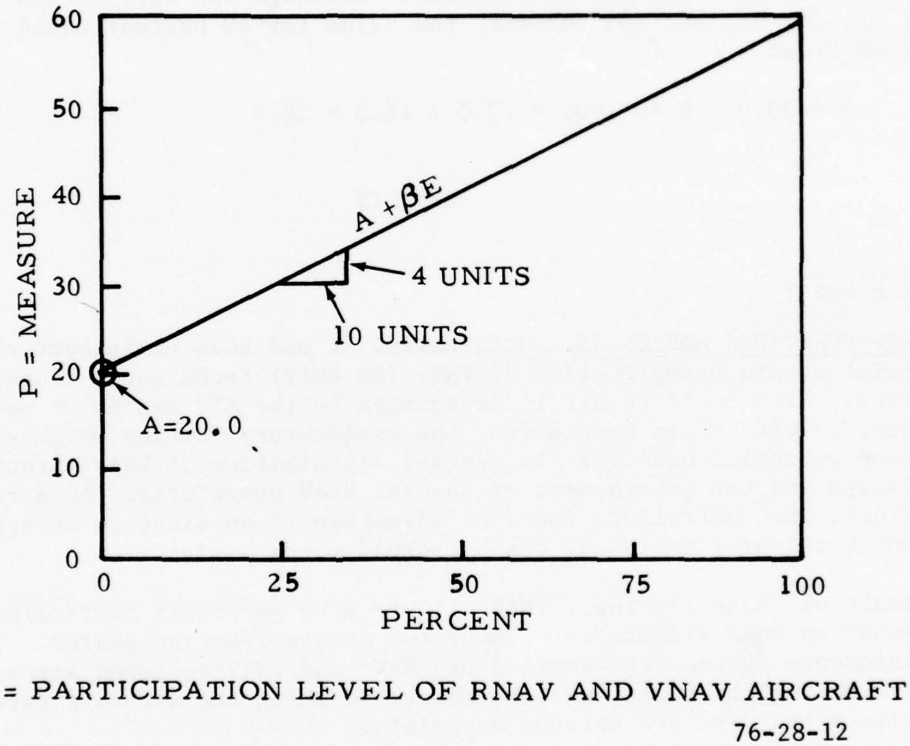


FIGURE 12. EXAMPLE OF REGRESSION RELATIONSHIP

The value of this method of representing the data lies in the fact that a general statement has been made concerning the mathematical relationship of the measures analyzed and the level of RNAV/VNAV participation allowing estimation of the value of the measures for values of the participation level not specifically included in the experiment. For instance, assume that the above relationship,

$$P = 20.0 + 0.40E$$

were the result of a regression analysis. Although the only levels tested were 0, 25, 50, 75, and 100 percent, the value for 40 percent could be determined from:

$$P = 20.0 + 0.40\ (40) = 20.0 + 16.0 = 36.0$$

RESULTS

OBJECTIVE DATA.

RNAV/VNAV *FUNCTIONS AND USAGE*. Originally, it had been envisioned that there could exist a unique application of VNAV (3D RNAV) techniques, routes, and procedures, which could result in advantages to the ATC system or user. Therefore, an effort was made during the exploratory portion of this study to develop potential uses for the special capabilities of VNAV through airspace design and the development of special VNAV procedures. As a result of this effort, the controllers found no advantage to an airspace design based upon VNAV gradients, including the "stacked" route design.

As a result of these findings, VNAV flights were generally controlled in the same manner as RNAV flights throughout the data collection period. The primary difference between the actions of RNAV- and VNAV-equipped aircraft, as simulated during the tests, was the manner in which the aircraft performed their climbs and descents between waypoints.

In order to assist in any possible determination of the capabilities which avionics equipments should possess in order to perform the functions which would be most used in the terminal environment, the RNAV/VNAV functions used by the controllers during this simulation were tabulated. The results are shown in table 3.

TABLE 3. CONTROLLER UTILIZATION OF RNAV/VNAV FUNCTIONS

Function	Times
Direct to Waypoint	3,037
Offset	2,649
Resume Navigation	1,959
Cancel Offset	1,683
Delay Fan	0

As indicated by the table, the controllers made extensive use of all the functions available to them with the exception of the programmed "delay fan." This is not to say that this particular function could not be useful or beneficial in the future, when a "metering and spacing" system has been developed. However, in today's ATC environment, the controllers found that they could delay aircraft more effectively by use of the offset function and subsequent cancellation of the offset by use of a direct-to-waypoint instruction as shown by figure 13, the difference between the two methods being that the delay fan function required the controller to specify a specific distance to offset. Without computer assistance, it was not possible for the controller to calculate this distance accurately. By use of the offset direct-to-waypoint tactic, the controller could duplicate, to a large extent, a series of radar vector maneuvers. He would do this by issuing a left or right offset of an arbitrary distance generally somewhat more than he felt really necessary. Then, when the desired delay had been accomplished, the offset was cancelled by a direct-to-waypoint instruction. This same series of instructions was used extensively by the controllers, in lieu of radar vectors, to sequence their traffic (figure 13).

The resume navigation function was available to reestablish an aircraft on the primary RNAV/VNAV route, or specified offset of the primary route, or, return a VNAV-equipped aircraft to a gradient, if its VNAV navigation had been previously disturbed. Although no count was made of the variations in the use of this instruction, it was determined during the controller debriefings,that the predominant use of this function was to return VNAV aircraft to their climb or descent gradients.

Included in the count of the offset function was the next-leg-offset. This maneuver received considerable use by the two Final Controllers, especially the Runway 22 Left Final Controller. It was used mainly to shorten or lengthen the downwind leg for the arrival aircraft from the south and west, as depicted in figure 14.

The direct-to-waypoint function was used extensively to shorten routes as well as the cancellation of offsets discussed earlier. The Final Controllers used this function to shortcut aircraft from the base leg to the final approach course. Waypoints had been placed at strategic locations on the final approach course in order that this maneuver could be accomplished.

<u>CONTROLLER WORKLOAD AND COMMUNICATIONS</u>. Controller communication activities were collected on magnetic tape and analyzed in order to determine if the use of RNAV/VNAV in a terminal area would reduce or increase the controller workload and to discover any indication of the possibility of increased controller productivity. The results of these data are shown in tables 4 and 5 and figures 15 and 16.

The results of the analysis indicate that each controller's communications workload decreased significantly as the percentage of RNAV/VNAV-equipped aircraft was increased.

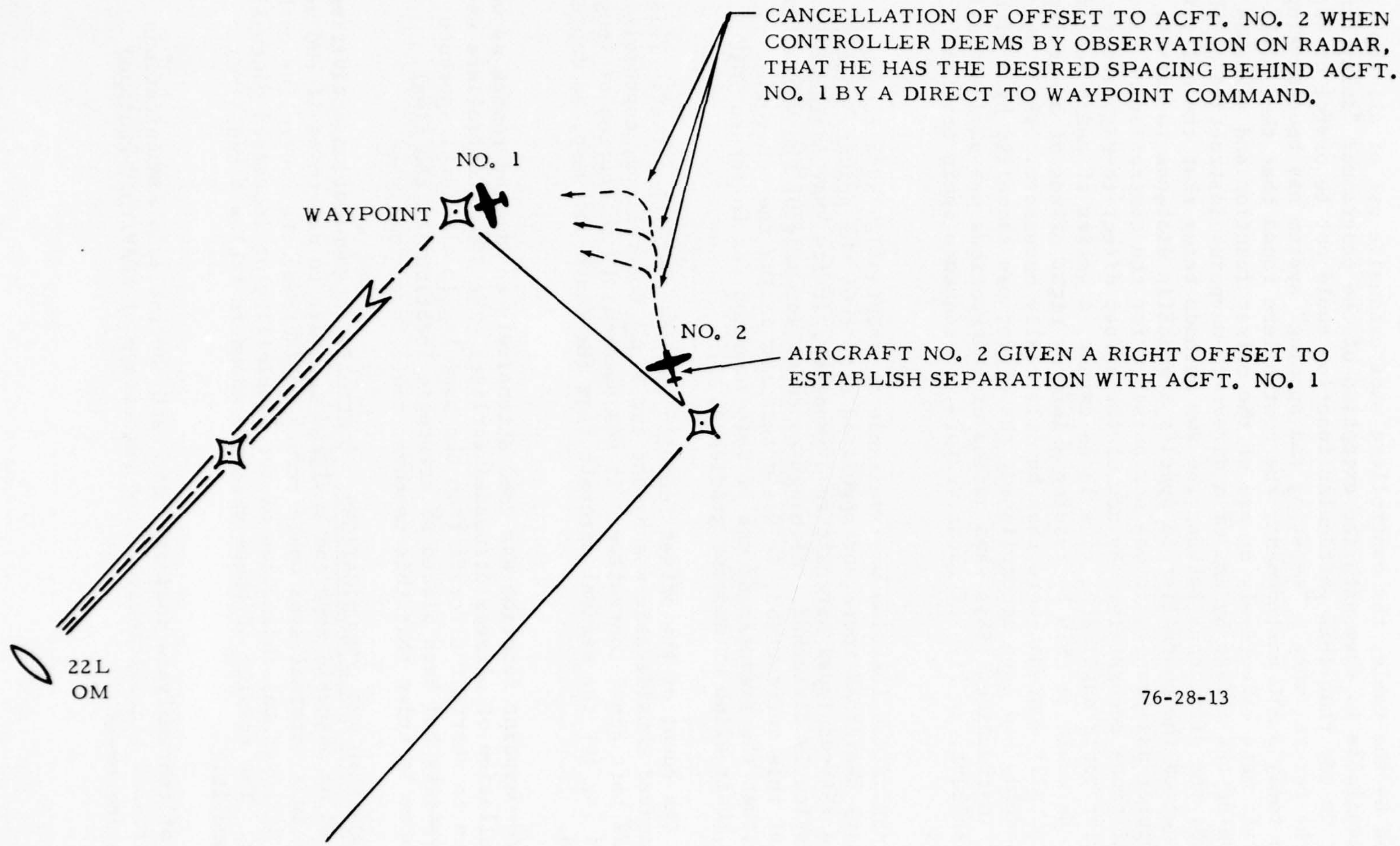


FIGURE 13. ILLUSTRATION OF THE USE OF THE "OFFSET" AND "DIRECT-TO-WAYPOINT" FUNCTIONS TO DUPLICATE THE "DELAY FAN" FUNCTION AS SUBSTITUTES FOR RADAR VECTORS

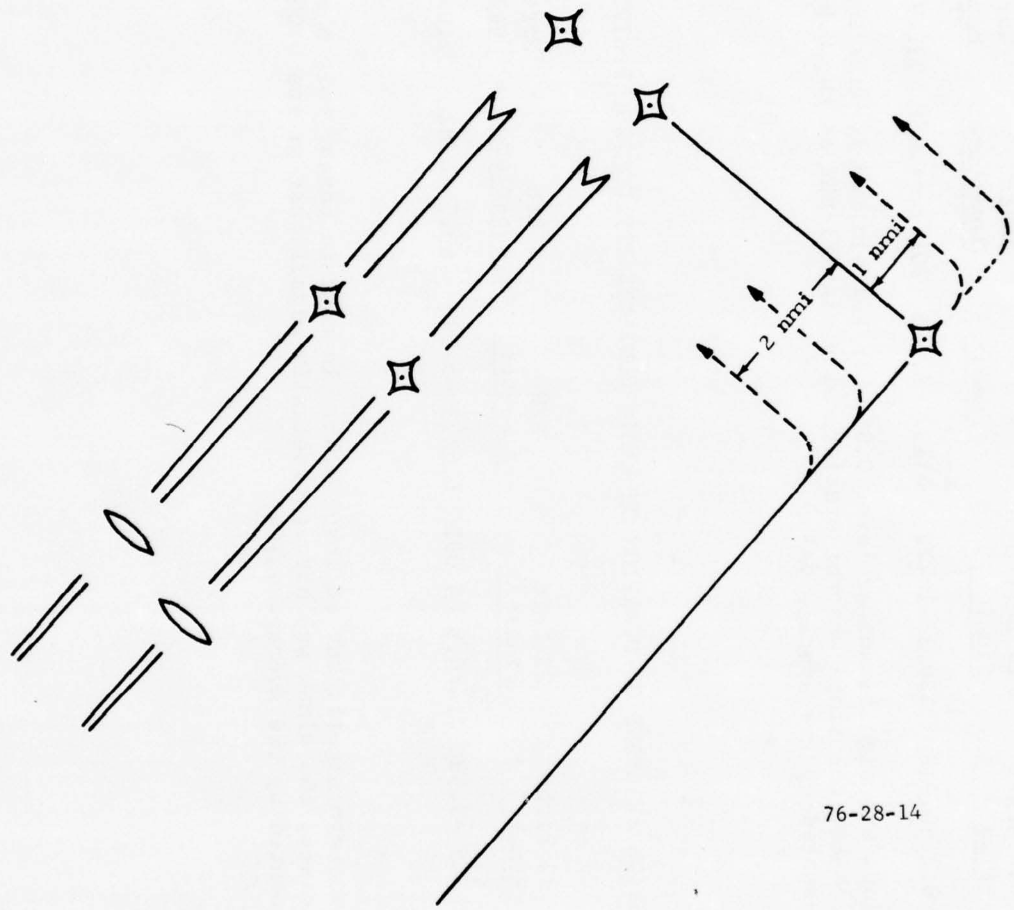


FIGURE 14. PRIMARY USAGE FOR NEXT-LEG OFFSET FUNCTION

TABLE 4. REGRESSION ANALYSES OF NUMBER OF RADIO CONTACTS PER CONTROL POSITION

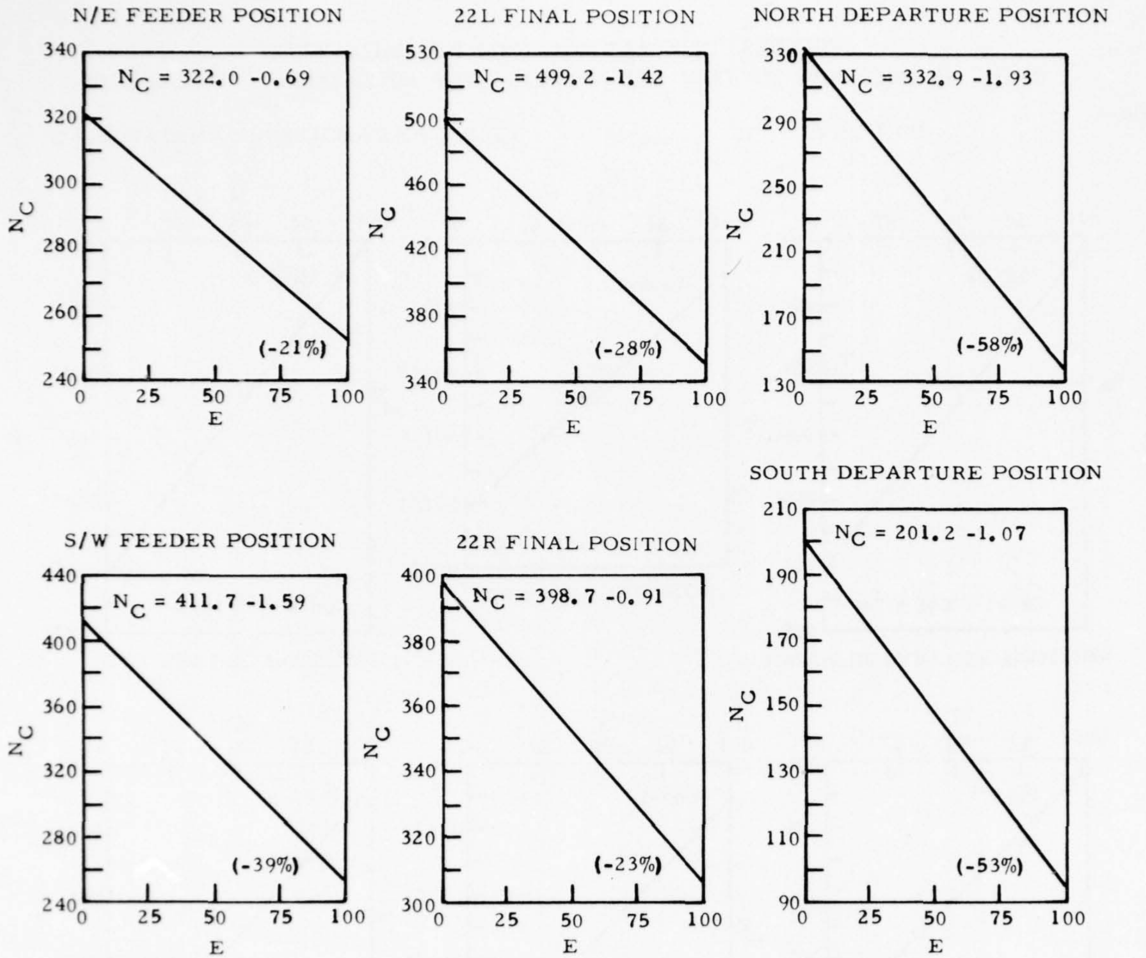
Position	N/E Feeder	22 Right Final	22 Left Final	S/W Feeder	South Departure	North Departure
Messages	322.0 -0.69E	398.7 -0.91E	499.2 -1.42E	411.7 -1.59E	201.2 -1.07E	332.9 -1.93E

Note: All regression equations are significant at level 0.05. In certain cases, only a single number is shown. For those cases, the slope was not statistically significant at the 0.05 level, and the data were best represented by the average value.

TABLE 5. REGRESSION ANALYSES OF DURATION OF RADIO CONTACTS PER CONTROL POSITION

Position	N/E Feeder	22 Right Final	22 Left Final	S/W Feeder	South Departure	North Departure
Messages Duration (Seconds)	960.3 -2.66E	1212.5 -3.58E	1476.8 -4.09E	1162.3 -5.09E	763.7 -4.82E	1104.3 -7.63E

Note: All regression equations are significant at level 0.05. In certain cases, only a single number is shown. For those cases, the slope was not statistically significant at the 0.05 level, and the data were best represented by the average value.



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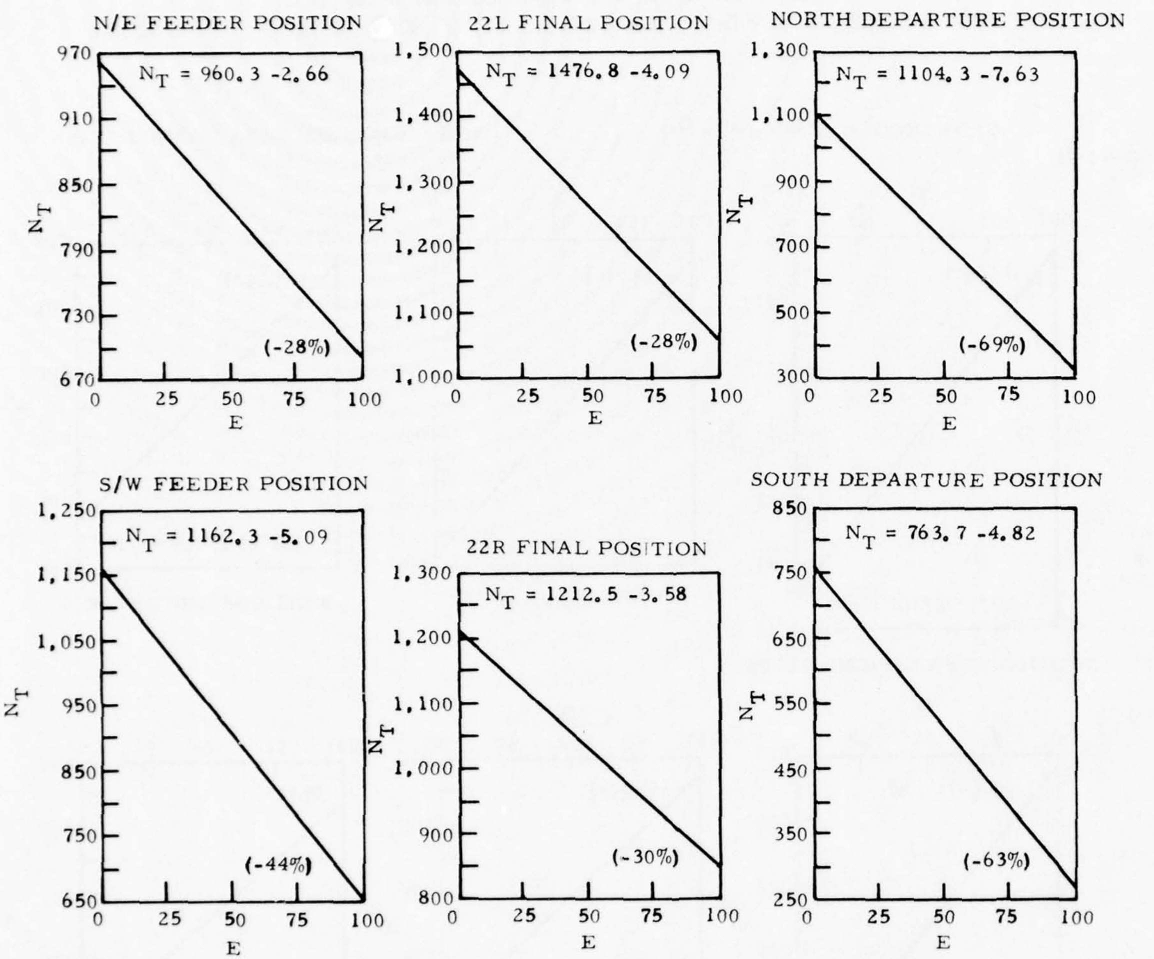
E = RNAV/VNAV, PARTICIPATION LEVEL

N_C = NUMBER OF CONTACTS

FIGURE 15. REGRESSION ANALYSES FOR THE AVERAGE NUMBER OF RADIO CONTACTS PER CONTROL POSITION PER RUN



E = RNAV/VNAV PARTICIPATION LEVEL

N_T = TALK TIME

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FIGURE 16. REGRESSION ANALYSES FOR THE AVERAGE DURATION OF RADIO TALK TIME PER POSITION PER RUN (SECONDS)

Again, a dramatic decrease in communication workload can be correlated with the increase in the RNAV/VNAV participation level.

In addition to the data with regression analysis presented above, averages of the number and duration of radio messages are depicted in tables 6 and 7, for the purpose of demonstrating how well the regression lines fit the actual averages at each participation level.

These data are presented along with an indication of the percentage of change in the number and duration of radio transmissions between the 100-percent radar-vector configuration and each RNAV/VNAV participation level up to 100 percent. No statistical tests were applied to these data; however, it can be seen that there are only four cases where the trend toward lower controller workload, as the percentage of equipped aircraft increased, showed a reversal. These data show a very dramatic reduction in some cases; such as the number and duration of transmissions for the North and South Departure Controllers which decreased by 59.8 percent and 58.7 percent, respectively, and radio talk time declined by 72.2 percent and 64.9 percent, respectively, when all aircraft were either RNAV or VNAV equipped. At the same time, all of the facility controllers combined experienced a reduction of 35.3 percent in the number of radio transmissions and 41.3 percent in the duration of radio talk time when all aircraft were either RNAV or VNAV equipped, as compared to the 100-percent radar-vectored traffic.

Data concerning the average number of radio transmissions, displayed in table 6, were collected by direct count of the number of times each controller depressed the "push-to-talk" switch on his microphone. The following data (table 8 and figures 17 and 18) were derived from a count of the number of specific control messages issued by each controller. These control messages are those which required keyboard entries by the DSF pilots to produce the required maneuvers by the simulated aircraft targets. Because of the differences in the measures employed, the data contained in table 8 cannot be directly compared with that in table 6.

The seven specific control messages (offset, cancel offset, direct waypoint, resume, radar vector, altitude change, and speed change) selected for individual analysis were those regarded to be the primary ones available to the controllers for the separation of traffic. The remaining messages were grouped under the miscellaneous category.

The first four messages are the RNAV/VNAV functions. As expected, the regression equations show that, in most cases, employment of these functions increased as the percentage of equipped aircraft in the system increased. The "resume" messages which were used mainly to reestablish VNAV aircraft on their gradients after a controller had disrupted their programmed climb/descent, experienced no significant increase in use by either the North/East feeder of the 22 Left Final Controller.

Use of the "radar vector" and "altitude change" messages decreased significantly as the number of equipped aircraft in the system increased. Radar vectors at the 100-percent level dropped by 90 percent for all control positions except the 22 Left Final Controller, which decreased by a very substantial 85.7 percent.

TABLE 6. AVERAGE NUMBER OF RADIO TRANSMISSIONS PER RUN

Participation Level*	N/E Feeder		22 Right Final		22 Left Final		S/W Feeder		North Departure		South Departure		Facility Total	
100% Radar	337.3	**	394.0	**	479.8	**	381.5	**	348.3	**	233.8	**	2,174.5	**
75% Radar	311.5	-7.6%	378.6	-3.9%	471.3	-1.8%	374.1	-1.9%	293.9	-15.6%	189.5	-18.9%	2,018.9	-7.2%
50% Radar	283.0	-16.1%	362.3	-8.0%	421.3	-12.2%	330.7	-13.3%	225.5	-35.3%	156.7	-33.0%	1,779.4	-18.2%
25% Radar	257.2	-23.7%	325.8	-17.3%	404.8	-15.6%	296.6	-22.3%	192.6	-44.7%	117.6	-49.7%	1,594.6	-26.7%
0% Radar	261.9	-22.4%	306.8	-22.1%	350.5	-26.9%	250.9	-34.2%	139.9	-59.8%	96.5	-58.7%	1,406.4	-35.3%

* 100% minus percentage radar = percentage of RNAV/VNAV-equipped flights.

** Percentage of change in the number of radio transmissions between 100% radar and the corresponding participation level.

TABLE 7. AVERAGE DURATION OF RADIO TALK TIME PER RUN

Participation Level*	N/E Feeder		22 Right Final		22 Left Final		S/W Feeder		North Departure		South Departure		Facility Total	
100% Radar	992.0	**	1,190.5	**	1,420.5	**	1,021.7	**	1,227.3	**	782.7	**	6,634.8	**
75% Radar	917.9	-7.5%	1,122.8	-5.7%	1,003.6	-29.4%	1,072.1	+4.7%	943.3	-23.2%	698.3	-10.8%	5,757.8	-13.2%
50% Radar	825.7	-16.8%	1,058.0	-11.1%	1,279.5	-9.9%	892.2	-12.7%	686.7	-44.1%	587.7	-24.9%	5,329.7	-19.7%
25% Radar	682.8	-31.2%	920.1	-22.7%	1,200.1	-15.6%	818.4	-19.9%	544.6	-55.6%	401.3	-48.7%	4,567.3	-31.2%
0% Radar	739.0	-25.5%	860.6	-27.7%	1,045.7	-26.4%	632.0	-38.2%	341.2	-72.2%	274.3	-64.9%	3,892.7	-41.3%

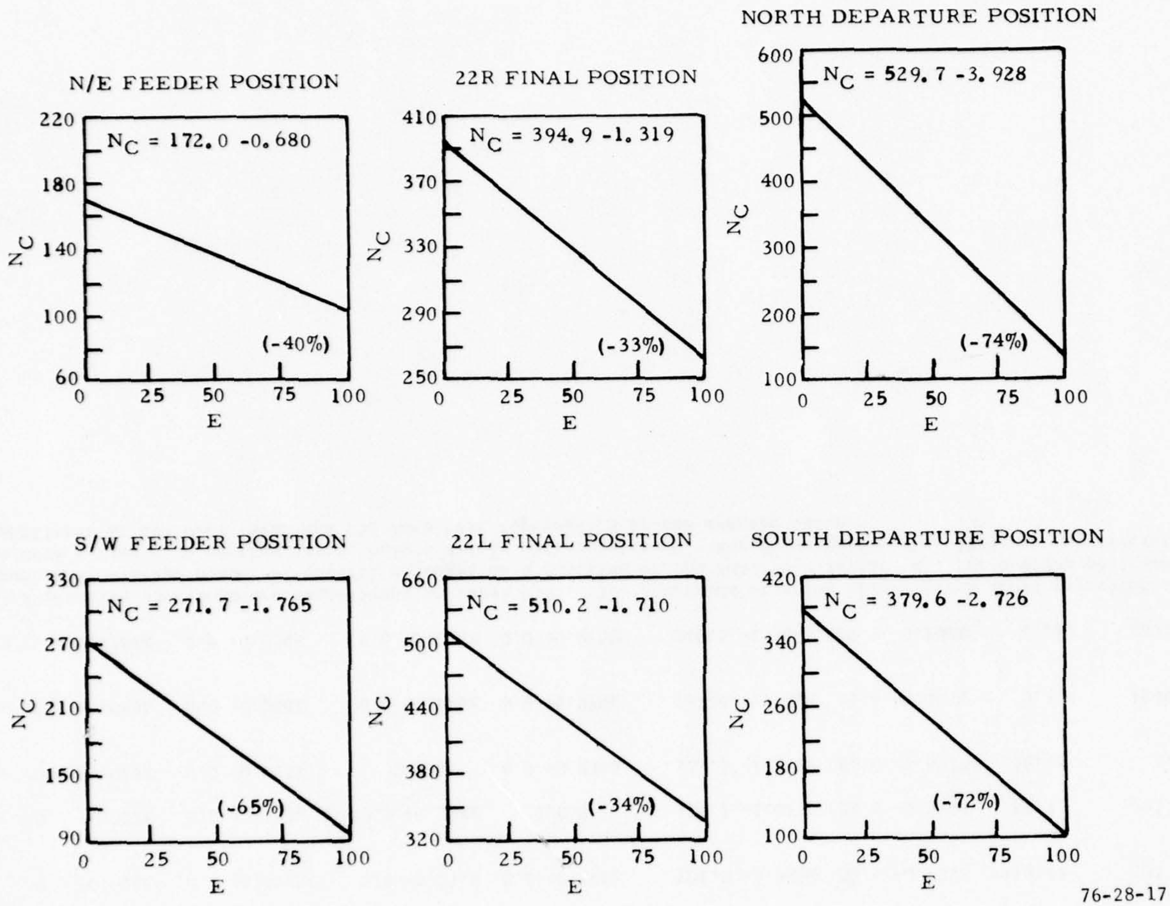
* 100% minus percentage radar = percentage of RNAV/VNAV-equipped flights.

** Percentage of change in the duration of radio talk time between 100% radar and the corresponding participation level.

TABLE 8. REGRESSION ANALYSES OF CONTROL MESSAGES PER CONTROL POSITION

	Messages								
Position	Offset	Cancel Offset	Direct Waypoint	Resume Flight Plan	Radar Vector	Altitude Change	Speed Change	Miscellaneous	Total
N/E Feeder	0.0 +0.138E	0.0 +0.93E	0.0 +0.027E	1.150	58.3 -0.560E	43.7 -0.403E	71.75	0.117	172.0 -0.680E
22 Right Final	0.0 +0.024E	0.0 +0.022E	0.0 +0.251E	0.0 +0.146E	101.3 -0.983E	39.4 -0.122E	119.47	135.1 -0.681E	394.9 -1.319E
22 Left Final	0.0 +0.022E	0.0 +0.153E	0.0 +0.388E	2.050	188.7 -1.617E	95.8 -0.529E	94.3	121.9 -0.204E	510.2 -1.710E
S/W Feeder	0.0 +0.079E	0.0 +0.055E	0.933	0.0 +0.034E	121.5 -1.129E	85.6 -0.817E	58.46	1.0 +0.021E	271.7 -1.765E
South Departure	0.0 +0.085E	0.0 +0.046E	0.0 +0.026E	0.0 +0.094E	137.6 -1.330E	56.4 -0.383E	0.316	183.1 -1.255E	379.6 -2.726E
North Departure	0.0 +0.108E	0.0 +0.054E	0.0 +0.036E	0.0 +0.085E	240.5 -2.264E	100.9 -0.732E	0.117	189.1 -1.288E	529.7 -3.928E

Note: All regression equations are significant at level 0.05. The equations or point values given above represent the expected or average number of control messages as a function of the RNAV/VNAV level, "E", for a given position during the data period. In certain cases, only a single number is shown. For those cases, the slope was not statistically significant at the 0.05 level and the data best represented by the average value.



E = RNAV/VNAV PARTICIPATION LEVEL N_C = NUMBER OF CONTROL MESSAGES

FIGURE 17. REGRESSION CHARTS OF TOTAL NUMBER OF CONTROL EFFORTS PER RUN BY CONTROL POSITION

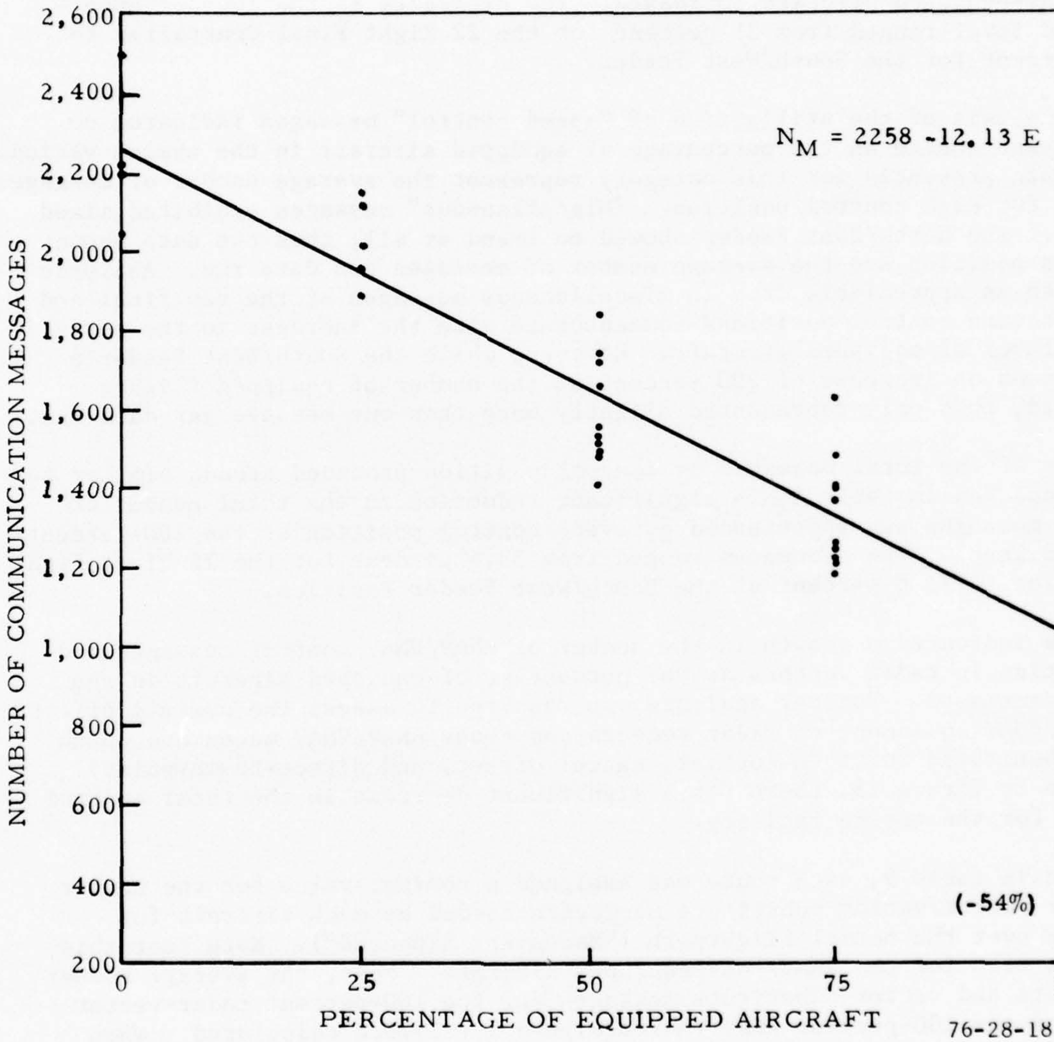


FIGURE 18. PLOT OF THE REGRESSION ANALYSIS OF TOTAL CONTROL MESSAGES FOR THE FACILITY

Inasmuch as the terminal route structure used in this simulation was designed to take advantage of the fact that the RNAV/VNAV aircraft could control their own climbs/descents, all control positions experienced a significant decline in the number of "altitude change" instructions issued as the percentage of RNAV/VNAV-equipped aircraft increased. The decreases at the 100-percent-equipped level ranged from 31 percent for the 22 Right Final Controller to 95.4 percent for the South/West Feeder.

Since analysis of the utilization of "speed control" messages indicated no significant change as the percentage of equipped aircraft in the system varied, those data presented for this category represent the average number of messages per run for each control position. "Miscellaneous" messages exhibited mixed results. The North/East Feeder showed no trend at all, thus the data shown for this position are the average number of messages per data run. Analysis indicated an appreciable drop in miscellaneous messages at the two final and two departure control positions commensurate with the increase in the participation level of equipped aircraft. However, while the South/West Feeder's data showed an increase of 200 percent as the number of equipped flights increased, this only represented slightly more than one message per data run.

Analysis of the total messages by control position produced trends similar to those depicted in table 6. A significant reduction in the total number of control messages was experienced by every control position at the 100-percent-equipped level. The decreases ranged from 33.4 percent for the 22 Right Final Controller to 71.8 percent at the South/West Feeder Position.

Analysis indicated a growth in the number of RNAV/VNAV control messages and a reduction in radar vectors as the percentage of equipped aircraft in the system increased. Further analysis was required to assess the overall effect of RNAV/VNAV equipment on radar vectors and those RNAV/VNAV maneuvers which were substituted for them (offset, cancel offset, and direct-to-waypoint). As shown by figure 18, there was a significant decrease in the total control efforts for the entire facility.

As shown in table 9, each route was assigned a nominal value for the number of radar vector/vector substitute maneuvers needed by each aircraft for guidance over the normal flightpath ("Maneuvers Expected"). Note that this value is zero for the RNAV/VNAV-equipped aircraft. Next, the average number of vectors and vector substitute messages for the 100-percent radar-vector level and the 100-percent RNAV/VNAV-equipped level were calculated. When the "vectors expected" value was deducted from the average number of actual vector/vector substitute maneuvers, the remainder represented the average number of extra maneuvers experienced on a per aircraft basis. Without exception, every route evidenced a high decline in the number of vector/vector substitute maneuvers. Arrival maneuvers decreased by 84 percent, departures by 79 percent, and the facility, as a whole, by 82 percent.

In addition to the communications data and analyses presented, the data were also analyzed on a per aircraft basis by control position. Table 10 and figures 19 and 20 depict the regression analysis for the average number of

TABLE 9. RESIDUAL MANEUVERS PER KEY FLIGHT

Route Number	Equipment	Vector/Vector Substitutes	Number of Aircraft	Average Maneuvers	Maneuvers Expected*	Residual Maneuvers
J201	Radar	339	132	2.57	1	1.57
	RNAV/VNAV	29	263	0.11	0	0.11
J202/203	Radar	305	130	2.35	1	1.35
	RNAV/VNAV	37	268	0.13	0	0.13
J204	Radar	695	118	5.89	3	2.89
	RNAV/VNAV	172	241	0.71	0	0.71
J205	Radar	542	118	4.59	2	2.59
	RNAV/VNAV	90	241	0.37	0	0.37
Total Arrivals	Radar	1,881	498	3.78	1.75	2.03
	RNAV/VNAV	328	1,013	0.32	0	0.32
J301	Radar	237	55	4.31	3	1.31
	RNAV/VNAV	45	111	0.41	0	0.41
J302	Radar	285	63	4.52	3	1.52
	RNAV/VNAV	95	127	0.75	0	0.75
J303	Radar	191	119	1.61	1	0.61
	RNAV/VNAV	2	228	0.01	0	0.01
J304	Radar	59	28	2.11	1	1.11
	RNAV/VNAV	12	65	0.18	0	0.18
J305	Radar	116	40	2.90	2	0.90
	RNAV/VNAV	19	77	0.25	0	0.25
J306	Radar	140	48	2.91	2	0.91
	RNAV/VNAV	23	96	0.24	0	0.24
J501	Radar	242	66	3.67	2	1.67
	RNAV/VNAV	15	129	0.12	0	0.12
J502	Radar	246	59	4.17	3	1.17
	RNAV/VNAV	12	123	0.10	0	0.10
Total Departures	Radar	1,516	478	3.17	2.04	1.11
	RNAV/VNAV	223	956	0.23	0	0.23
Facility Total	Radar	3,397	976	3.48	1.89	1.59
	RNAV/VNAV	551	1,967	0.28	0	0.28

Note: For a diagram of route numbers, refer to figure 11.

*Does not include initial heading insturctions or STAR assignments for arrivals and heading/SID assignments for departures.

TABLE 10. REGRESSION ANALYSES OF TOTAL COMMUNICATIONS MESSAGES PER AIRCRAFT

Position	Number of Radio Contacts per Aircraft	Duration of Radio Messages per Contact	Duration of Radio Contacts per Aircraft
North/East Feeder	4.79 -0.0096E	2.99 -0.0023E	14.27 -0.0374E
22 Left Final	6.11 -0.0143E	3.08 -0.0036E	18.58 -0.0559E
22 Right Final	8.39 -0.0245E	3.02	24.84 -0.0717E
South/West Feeder	6.81 -0.0272E	2.89 -0.0031E	19.22 -0.0866E
South Departure	3.38 -0.0182E	3.76 -0.0085E	12.82 -0.0812E
North Departure	5.53 -0.0324E	3.49 -0.0100E	18.36 -0.1280E
Facility Average	5.82 -0.0210E	3.13 -0.0035E	17.94 -0.0754E

Note: All regression equations are significant at level 0.05. In certain cases, only a single number is shown. For those cases, the slope was not statistically significant at the 0.05 level, and the data were best represented by the average value.

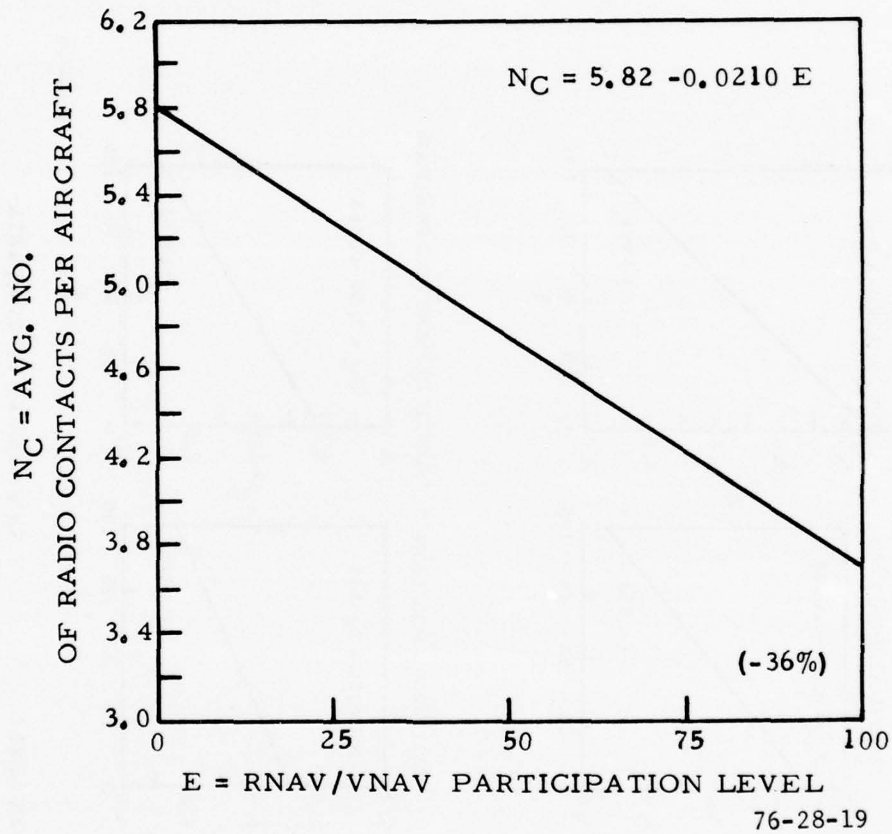
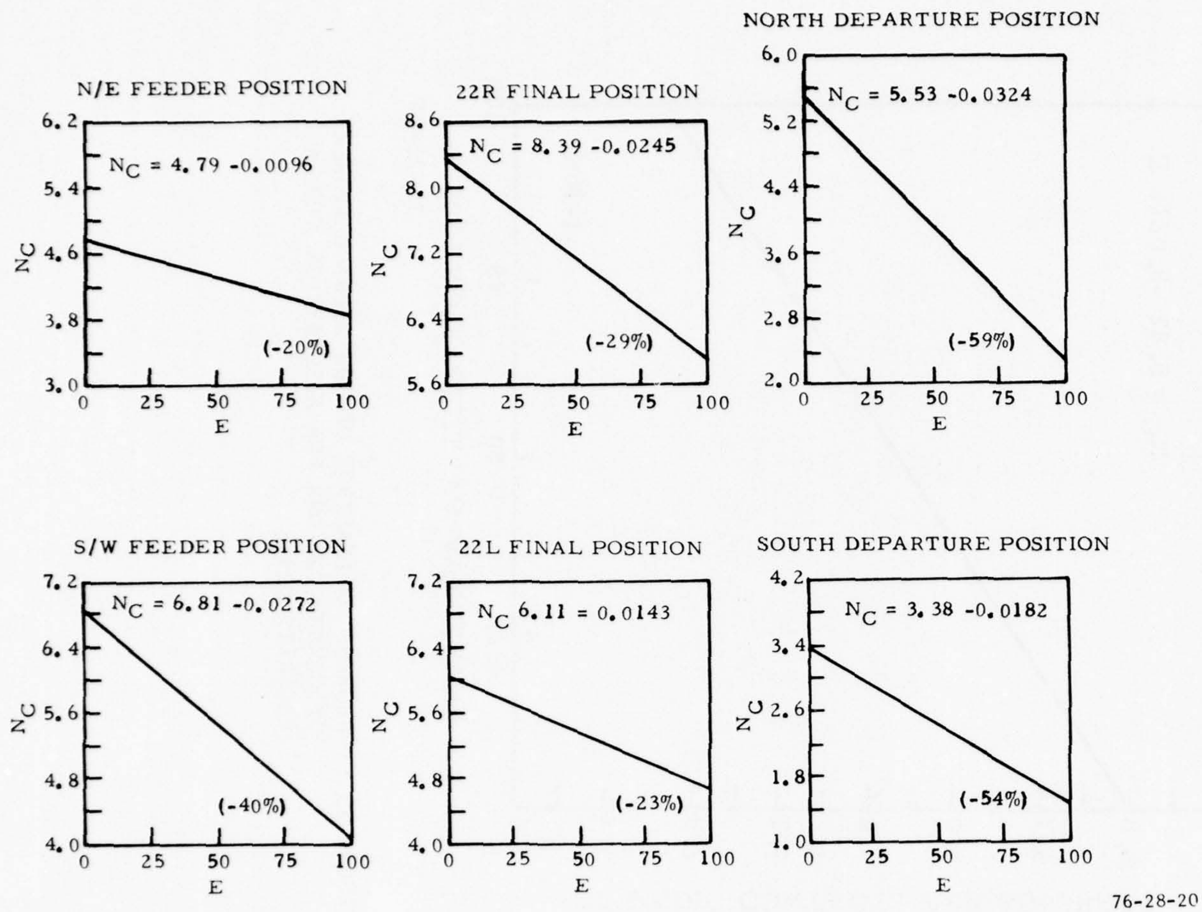


FIGURE 19. REGRESSION ANALYSES OF THE AVERAGE NUMBER OF COMMUNICATIONS PER AIRCRAFT ON A TOTAL FACILITY BASIS



E = RNAV/VNAV PARTICIPATION LEVEL

N_C = NUMBER OF CONTACTS

FIGURE 20. REGRESSION CHARTS OF THE NUMBER OF RADIO CONTACTS PER AIRCRAFT PER RUN

contacts per aircraft and the average duration of each contact per aircraft and per contact. The trend discovered in this analysis follows the pattern present in the analyses of the other communications data. Generally speaking, as the number of equipped aircraft in the sample increased, there was a significant decrease in both the number and duration of controller-to-pilot messages.

For all control positions, the average number of contacts per aircraft decreased. The reduction averaged 53.8 percent for the South Departure Controller and 58.6 percent for the North Departure Controller. Even the smallest reduction experienced by the North/East Feeder Position was a significant 20 percent.

The duration of talk time per contact did not exhibit as high a percentage of decrease as some of the other communication measures. Nevertheless, with the exception of the 22 Left Final Controller, every position showed a statistically significant reduction. Both departure controllers reduced the length of their average message by more than 20 percent, while reductions on the other positions ranged from 7.7 percent to 11.7 percent. The overall reduction for the facility was 11.1 percent.

When the duration of radio contacts was analyzed on a per aircraft basis, an even greater reduction was found. The smallest decrease occurred on the North/East Feeder Position where the duration of radio contacts per aircraft was reduced by more than 26 percent. The greatest decline was found at the North Departure Controller's Position, where the duration of radio contacts dropped by nearly 70 percent. The total facility benefited by a 42.0-percent decrease in duration per aircraft talk time.

ROUTE MEASURES. Distance flown, time in system, delay, and fuel consumption data were collected on the 64-key arrival and 80-key departure flights. Analysis was performed to determine the effects on the ATC system user which could occur from the employment of RNAV/VNAV in the terminal area. Data are presented by the individual arrival and departure routes, as well by an aggregate of all arrival and departure routes. In order to reduce the number of cases to be analyzed and increase the number of available data points, similar arrival routes were grouped by feeder fixes, while certain departure routes were combined according to direction of flight. Nominal route distances were identical for RNAV/VNAV and radar-vectored aircraft on any given route.

The coding used for the arrival and departure routes is shown in table 11. A single alpha character is used to identify the airport with which the route is associated while the three numerics indicate the route's function (arrival or departure) identification number. These coded routes were used to facilitate comparison between the proposed route design shown in appendix B and the modified designs (figures 9 and 11).

DISTANCE FLOWN. The "distance flown" anlaysis is contained in table 12 and the statistical relationships determined by that analysis are shown graphically by figures 21 and 22. Both RNAV and VNAV were handled basically in the same

TABLE 11. ROUTE IDENTIFICATION CODES

J = John F. Kennedy (JFK) Airport L = LaGuardia (LGA) Airport,
E = Newark (EWR) Airport

Series Number	Route Utilization
200	Arrivals
300	Departures
500	High-Performance Departures

TABLE 12. REGRESSION ANALYSES OF DISTANCE FLOWN PER KEY FLIGHT

Route	Regression Equation or Average Distance Nautical Miles (nmi)	Kilometers (km)
Arrivals (distance measured form start fix to runway)		
J201	837.6 -040E	1,551.2 -0.74E
J202/203	677.09	1,253.97
JJ204	1,060.7 -0.65E	1,964.42 -1.20E
J205	1,026.55	1,901.17
Overall	3,667.3 -1.13E	6,791.84 -2.093E
Departures (distance measured from runway to exit fix)		
J301/501	1,166.40	2,160.17
J302/502	·938.73	1,738.77
J303	836.81	1,549.77
J304/305/306	577.36	1,069.27
Overall	3,519.3	6,517.74

Note: All regression equations are significant at level 0.05. In certain cases, only a single number is shown. For those cases, the slope was not statistically significant at the 0.05 level, and the data were best represented by the average value.

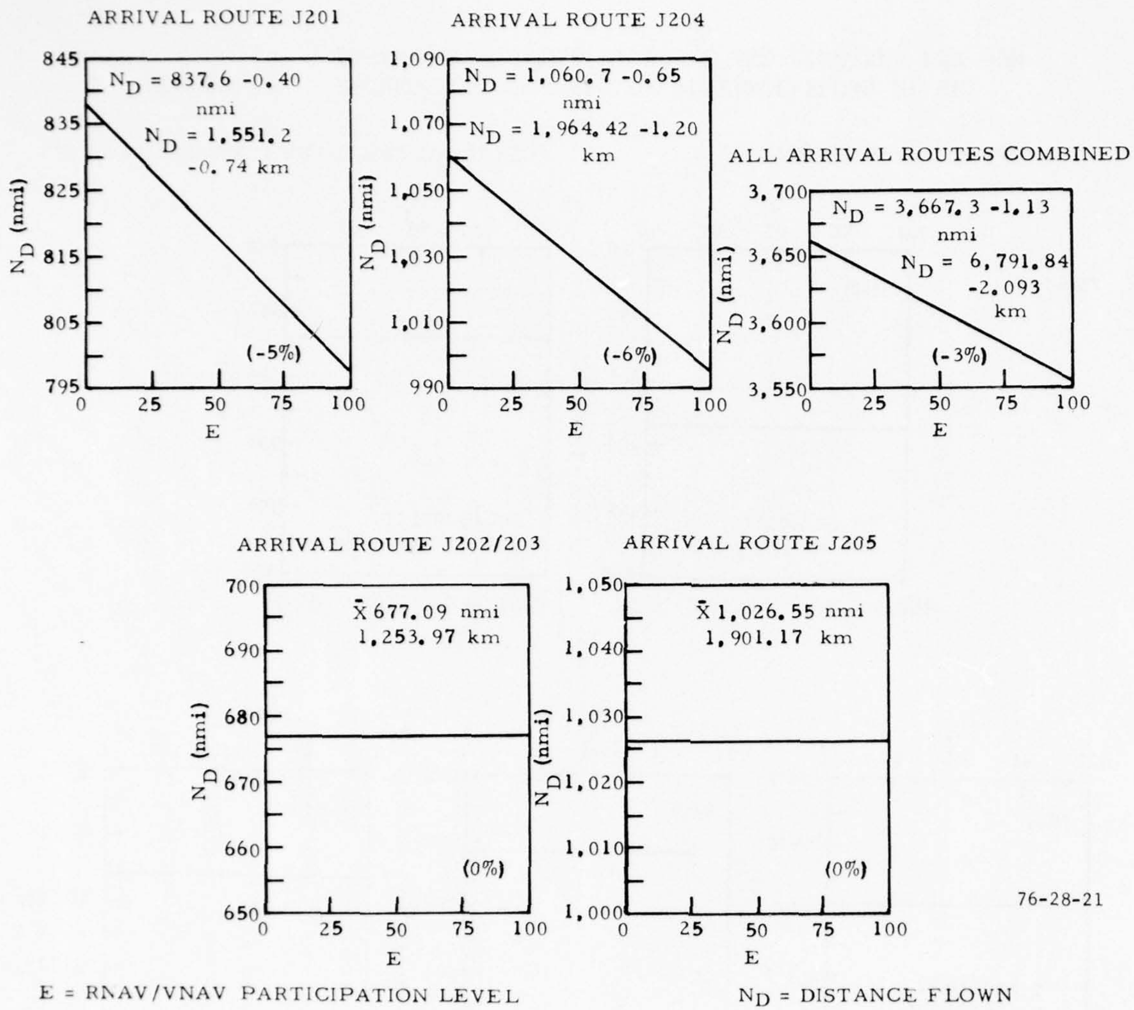
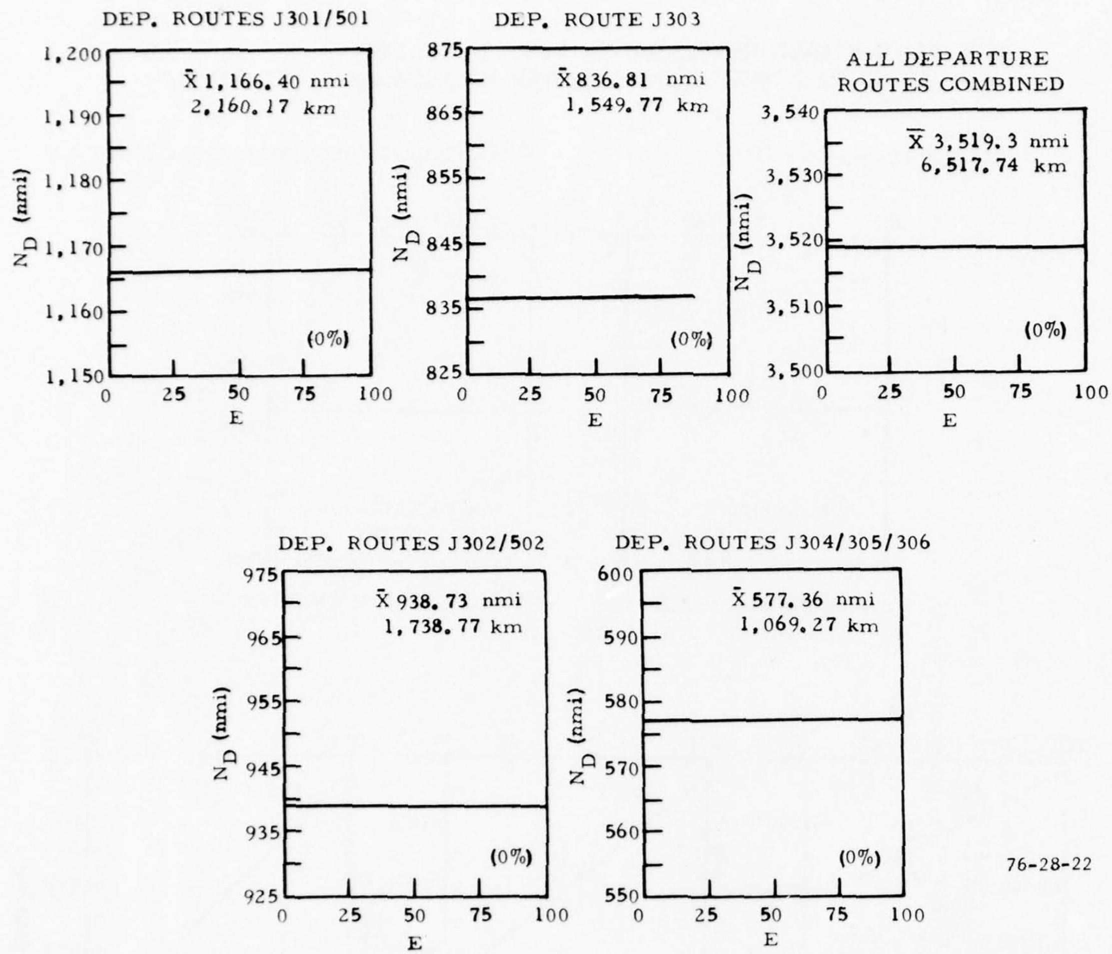


FIGURE 21. REGRESSION ANALYSES OF DISTANCE FLOWN BY KEY ARRIVAL FLIGHTS BY ROUTE AND COMBINED PER RUN



E = RNAV/VNAV PARTICIPATION LEVEL

N_D = DISTANCE FLOWN

FIGURE 22. REGRESSION ANALYSES OF DISTANCE FLOWN BY KEY DEPARTURE FLIGHTS BY ROUTE AND COMBINED PER RUN

manner by the controllers; the only difference being in the method by which the VNAV aircraft climbed/descended to achieve their altitude restrictions. The data for the RNAV and VNAV aircraft were combined and analyzed together. The results of the regression analysis show the difference between the average distance traveled by radar-vectored aircraft compared to the distance flown by RNAV/VNAV-equipped aircraft over the same route. When analysis indicated no statistically significant difference at the 0.05 level in the distance flown by the equipped and nonequipped aircraft, the graphic representation of that particular route of flight took on the appearance of a horizontal line which represents the average distance flown by all aircraft over that route (figure 21).

Arrivals. The analysis presented in table 12 and figure 21 shows that equipped aircraft, on the average, flew a shorter distance than nonequipped aircraft on two out of the four arrival routes. No statistically significant difference was discovered over the other two routes. On route J201, at the 0-percent-equipped participation level, the estimated regression value of the distance flown by all arrivals was 838 nmi (1552 km) per run. At the 100-percent-equipped participation level, all aircraft flew a total of 40 nmi (74.08 km) or 4.8 percent less distance. Route J204 also recorded a statistically significant trend for the equipped aircraft to fly a shorter distance than the nonequipped as the participation level increased. Nonequipped aircraft flew 1,061 nmi (2965 km) over this route, while the equipped aircraft at the 100-percent participation level experienced 64.7 nmi (119.8 km) or a 6.3 percent reduction of this distance.

When all arrival routes were grouped together, the aggregate distance flown by all aircraft at the 0-percent-equipped participation level was 3,607 nmi (6680 km) per data run. At the 100-percent-equipped level, analysis shows that this distance was shortened by 111.8 nmi (207.1 km) or 3.1 percent. Visual analysis of the arrival route structure revealed that those two routes which showed a significant reduction in distance flown were better adapted to RNAV/VNAV shortcutting techniques (offset, direct-to-waypoint) than were the other two.

Departures. The analysis of the departure data presented in table 12 and figure 22 found no statistically significant trends existing between equipped and nonequipped aircraft as the participation level increased. Therefore, the data represent the average distance flown by all aircraft, over each given route, on a per run basis.

It is interesting to note that in the previous simulation, significant trends, in favor of nonequipped aircraft were discovered on certain departure routes. This was attributed to some of the controllers, who admitted that they more frequently "shortcut" the nonequipped aircraft because they had to provide navigational guidance for them at any rate. They felt that by shortening their course, they would be able to hand them off sooner and thereby reduce their workload. They did not shortcut the equipped aircraft, since this would have required an extra transmission. In this simulation, the controllers were encouraged to (and in fact did) shortcut their aircraft at every opportunity, whether equipped or not. Hence, the data indicate that the departure

controllers were able to shorten the flightpath of an aircraft just as efficiently whether it was being radar vectored or operating on RNAV/VNAV. However, the communications measures previously discussed indicate that the workload for this improved service is considerably less when the aircraft are RNAV/VNAV equipped.

TIME IN SYSTEM.

Arrivals. This was a measure of actual route flying time, once the aircraft had commenced its flight. The analysis of the arrival data correlates closely with the analysis of distance flown. It was found that the aircraft on J201 and J204 spent less time in the system as the RNAV/VNAV participation level increased (table 13). It was found that the arrivals from the east on J201 had an overall reduction in their total time in system of 30 minutes or 10.4 percent per run at the 100-percent-equipped participation level over the time in system of the nonequipped aircraft at the 0-percent participation level. Likewise, the arrivals on the route from the west, J204, averaged a total reduction of 25 minutes or 7.9 percent of time in system per run when the equipped level reached 100 percent. An aggregate of all arrival routes produced a total decrease in time in system of 71 minutes or 6.3 percent per run at the 100-percent-equipped level.

Departures. Again, as in the distance flown measures, analysis of the departure data for time in system produced no significant trends between radar-vectored and RNAV-equipped aircraft. There was, however, a significant increase found on all departure routes for VNAV-equipped aircraft at the 100-percent-equipped level over radar-vectored aircraft. From the distance-flown data, it was observed that there was no statistical trend for VNAV departures to fly a longer distance; thus, it seems apparent that the fixed gradient climb-profiles required by the DSF kept the VNAV-equipped aircraft at consistently slower speeds, thereby increasing the time spent traversing their departure routes. It is not conclusive that this would be a true indication of what could be expected to occur when actual aircraft fly gradients on departure SID's. It is possible that this phenonemon was the result of the aircraft profile data in the DSF software or of some general pilot/controller interaction which was not detected during analysis. Isolation of the cause seems impossible with the data from this simulation. Further simulation or flight testing might provide valuable insight into this problem.

OPERATION RATES.

Arrivals. The arrival data were subjected to a linear regression analysis. The regression equation shown in table 14 reveals that there was an increase of 2 1/2 arrivals per hour. This increase would seem to be the result of a more orderly flow of traffic from the feeder fixes, which resulted from the use of RNAV.

TABLE 13. TIME IN SYSTEM PER KEY FLIGHT

Regression Equations of Average Time in System

Arrivals

Route	Seconds
J201	17,208.9 -17.96E
F202/203	13,801.8
J204	18,718.8 -14.7E
J205	17,788.0
Overall	68,221.6 -43.0E

Departures

Route	Seconds
J301/501	14,333.7 +13.4 (VNAV)
J302/502	13,513.7 +11.1 (VNAV)
J303	13,636.2 +7.6 (VNAV)
J304/305/306	9,151.8 +6.1 (VNAV)
Overall	50,635.3 +38.2 (VNAV)

Note: All regression equations are significant at level 0.05. In certain cases, only a single number is shown. For those cases, the slope was not statistically significant at the 0.05 level and the data were best represented by the average value.

TABLE 14. REGRESSION ANALYSES OF OPERATIONS RATES*

Arrivals	76.59+0.25E
Departures	80.30
Facility Total	158.87

*Based on all the data points, including the 0-percent-equipped level. All regression equations are significant at level 0.05. In certain cases, only a single number is shown. For those cases, the slope was not statistically significant at the 0.05 level, and the data were best represented by the average value.

Departure. Departure data were treated and analyzed in the same manner as arrivals. The regression equation (table 14) failed to find statistically significant change in departure rates at any participation level. Since a departure is released relative to the position of a preceding aircraft, regardless of any consideration of airborne equipment, this result was expected.

Total Operations. The regression equation (table 14) applied to the facility operations rates showed no statistically significant change at any participation level.

START-POINT DELAY. Start-point delays occurred whenever the number of aircraft scheduled to enter the system exceeded system capacity. A regression analysis of start-point delay data can be found in table 15. Three of the four arrival routes showed a considerable reduction in start-point delay as the participation level of equipped aircraft increased to 100 percent. All of the arrival routes grouped together experienced a total of 5 1/2 hours or 34.4 percent reduction in delay time. Departure start-point delay time was not found to be significantly different for any level of participation except that the VNAV routes J302/502 experienced a total of 33 minutes or a 27.1-percent increase at the 100-percent-equipped participation level.

Closer analysis of this result, and the data which indicated no significant change in start-point delay time for route J205, produced no tangible reason for these trends to run counter to the general trend for this measure.

FUEL CONSUMPTION. Data concerning fuel consumption were only compiled at the three "pure" levels of participation (i.e., 100-percent radar vector, 100-percent RNAV, and 100-percent VNAV). Although the trends in these data seemed favorable to the equipped aircraft, especially VNAV, they were not statistically significant, even when tested at the 0.10 level.

RNAV/VNAV BROKEN REPORTS. The data presented in table 16 indicate (a) the ratio of the number of times equipped aircraft were taken off their horizontal navigation to the number of aircraft handled, and (b) the average time (in seconds) each aircraft was out of RNAV/VNAV status. As the regression analyses show, there was a lower incidence of "breaks" as the percentage of equipped aircraft increased. Generally, there was, however, no significant reduction in the length of time that the average aircraft was in a broken status.

TABLE 15. REGRESSION ANALYSES OF START-POINT DELAY PER KEY FLIGHT

Regression Equations of Average Delay Time

Route	Seconds
Arrivals	
J201	16,478.7 -103.80E
J202/203	12,333.9 -65.10E
J204	15,346.4 -31.20E
J205	13,527.6
Overall	57,550.9 -198.20E
Departures	
J301/501	10,684.4
J302/502	7,422.1 +20.10E
J303	6,192.2
J304/305/306	5,375.0
Overall	30,639.9

Note: All regression equations are significant at level 0.05. In certain cases, only a single number is shown. For those cases, the slope was not statistically significant at the 0.05 level and the data were best represented by the average value.

TABLE 16. RNAV/VNAV BROKEN REPORTS

Position	Number Broken	Average Break Time (Seconds)
N/E Feeder	0.0154	115.3
22 Right Final	0.0226	125.4
22 Left Final	0.3037	126.8
S/W Feeder	0.158 -0.0011E	58.0
South Departure	0.0779	120.2
North Departure	0.4145 -0.0024E	177.25
All	0.2163 -0.0012E	137.7

Note: The data presented in this table are valid only when the particiaption level of equipped aircraft is 25 percent or greater.

In regression, equations are significant at level 0.05. In certain cases, only a single number is shown. For those cases, the slope was not statistically significant at the 0.05 level, and the data were best represented by the average value.

TABLE 17. BROKEN VNAV GRADIENT REPORTS

Position	Number Broken	Average Break Time (Seconds)
N/E Feeder	0.0512	116.91
22 Right Final	0.4602	114.95
22 Left Final	0.8173	135.16
S/W Feeder	0.1719 -0.0010E	62.71
South Departure	0.2722	110.66
North Departure	0.766 -0.0042E	108.93 +0.533E
All	0.3529	132.0

Note: The data presented in this table are valid only when the participation level of equipped aircraft is 25 percent or greater.

In regression equations are significant at level 0.05. In certain cases, only a single number is shown For those cases, the slope was not statistically significant at the 0.05 level, and the data were best represented by the average value.

Table 17 illustrates the incidence of broken VNAV gradients and their duration. Overall, there was no significant reduction in occurrence or duration as the percentage of VNAV-equipped aircraft increased.

EFFECT OF TWO AVIONICS LEVELS. Another objective of this experiment was to determine if two levels of RNAV/VNAV avionics sophistication would cause problems for the controllers within the terminal area. Specifically, any effect on the airspace in the immediate vicinity of the two final approaches was of the greatest concern. It was found that the presence of low-level avionics did affect the spacing which the controllers had established on the downwind leg and were trying to maintain to the final approach courses. Figures 23, 24, 25, and 26 are examples of actual tracks flown by the simulated targets which show the wide variety of paths produced by the DSF simulator by application of the error model used throughout this simulation. The GAT simulators produced tracks similar to those of the DSF. There exists a probability that similar results will occur during actual flight involving varied levels of avionics sophistication and pilot training/experience.

Figure 23 depicts the flightpaths of two aircraft targets programmed with low-performance RNAV avionics. The first aircraft (dotted track) made a rather wide turn onto the base leg, overshooting the primary track, then turned early onto the ILS final approach course. The second aircraft (dashed track) was found to be operating to the left of the parent track from where it cut inside of the waypoint at the turn to the base leg and overshot the turn somewhat less than its predecessor. In this event, the second aircraft shortened the distance between itself and the first aircraft.

In figure 24, the dotted track depicts the flightpath of a simulated aircraft target with sophisticated (high level) avionics performance, and the dashed track, that of a target of low-performance capability. As shown, the more sophisticated equipment caused its aircraft to fly an almost perfect flightpath. Note that the turn anticipation feature caused the aircraft to turn slightly inside of the waypoints. The aircraft which simulated low-performance avionics, while holding to course rather well, did make some excursions from course, especially in the turns. In this example, there was less impact upon the interval between the two aircraft.

Figure 25 depicts the flightpaths of high-performance equipment (dots) and low-performance equipment (dashes). As in the previous figure, the more sophisticated equipment exhibited almost perfect tracking and turn anticipation. Meanwhile, the less sophisticated equipment tracked to the left of course on the downwind leg, which was followed by a shortened turn onto the base leg. Again, this combination of tracks adversely affected the aircraft separation established by the controllers. In both figures 24 and 25, the aircraft with the lower level equipment made a wider turn to the ILS final approach course which gained back some of the spacing lost on the base leg.

Figure 26 shows the flightpaths of two low-performance-level RNAV-equipped aircraft. Again it is apparent that the interval established between the aircraft by the controllers increased, because of the characteristics of the

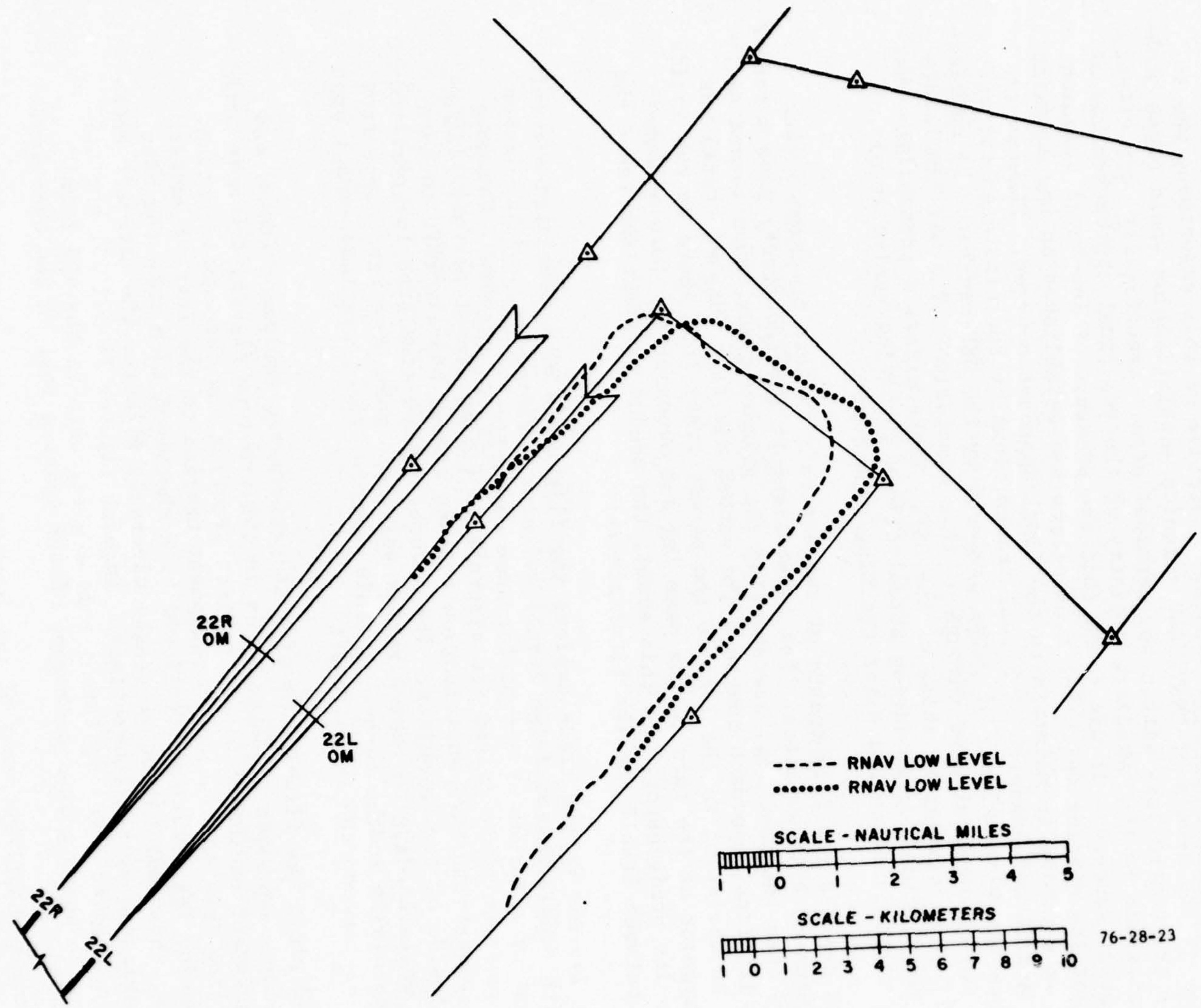


FIGURE 23. SIMULATED TARGET TRACKS (EXAMPLE 1)

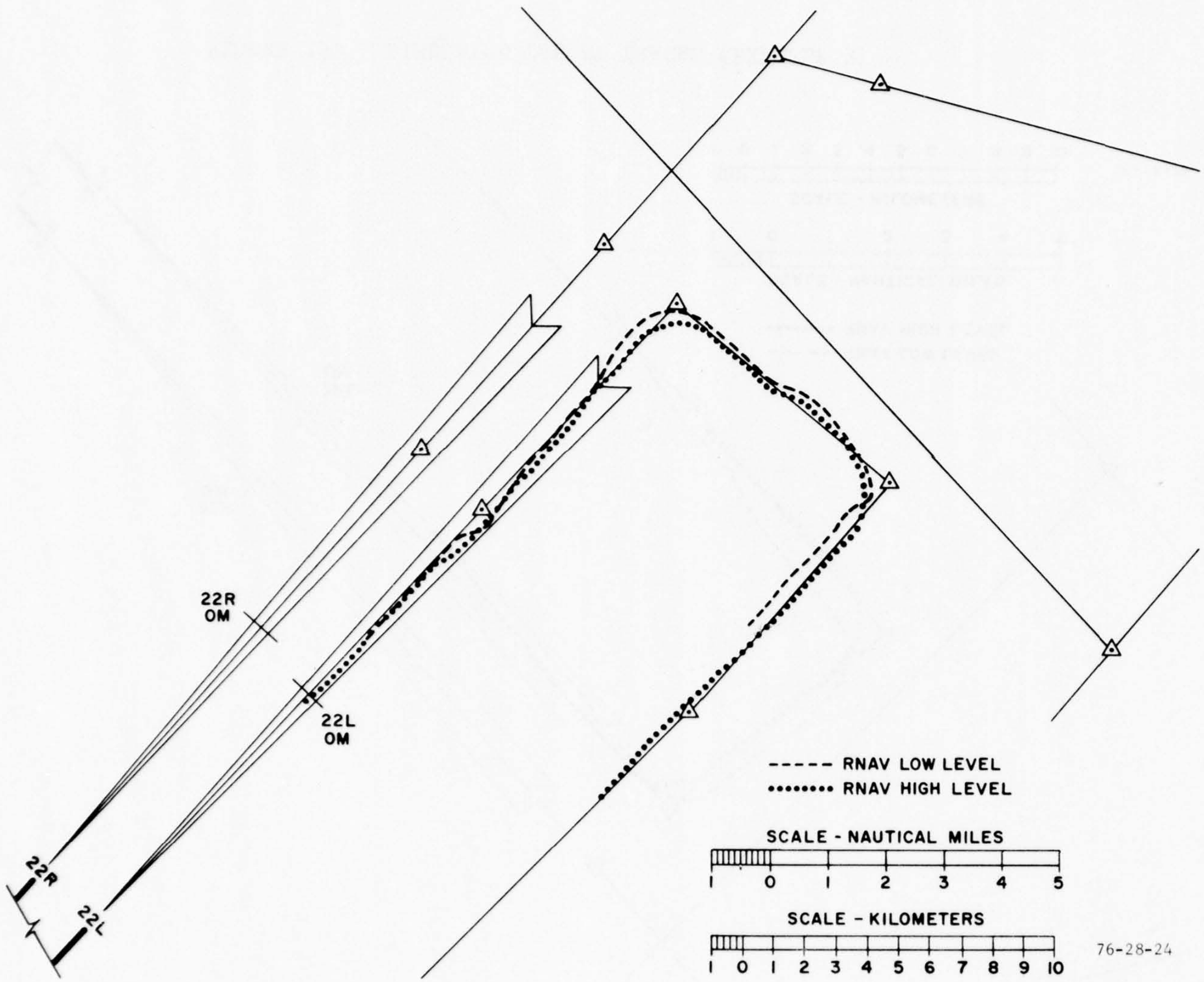


FIGURE 24. SIMULATED TARGET TRACKS (EXAMPLE 2)

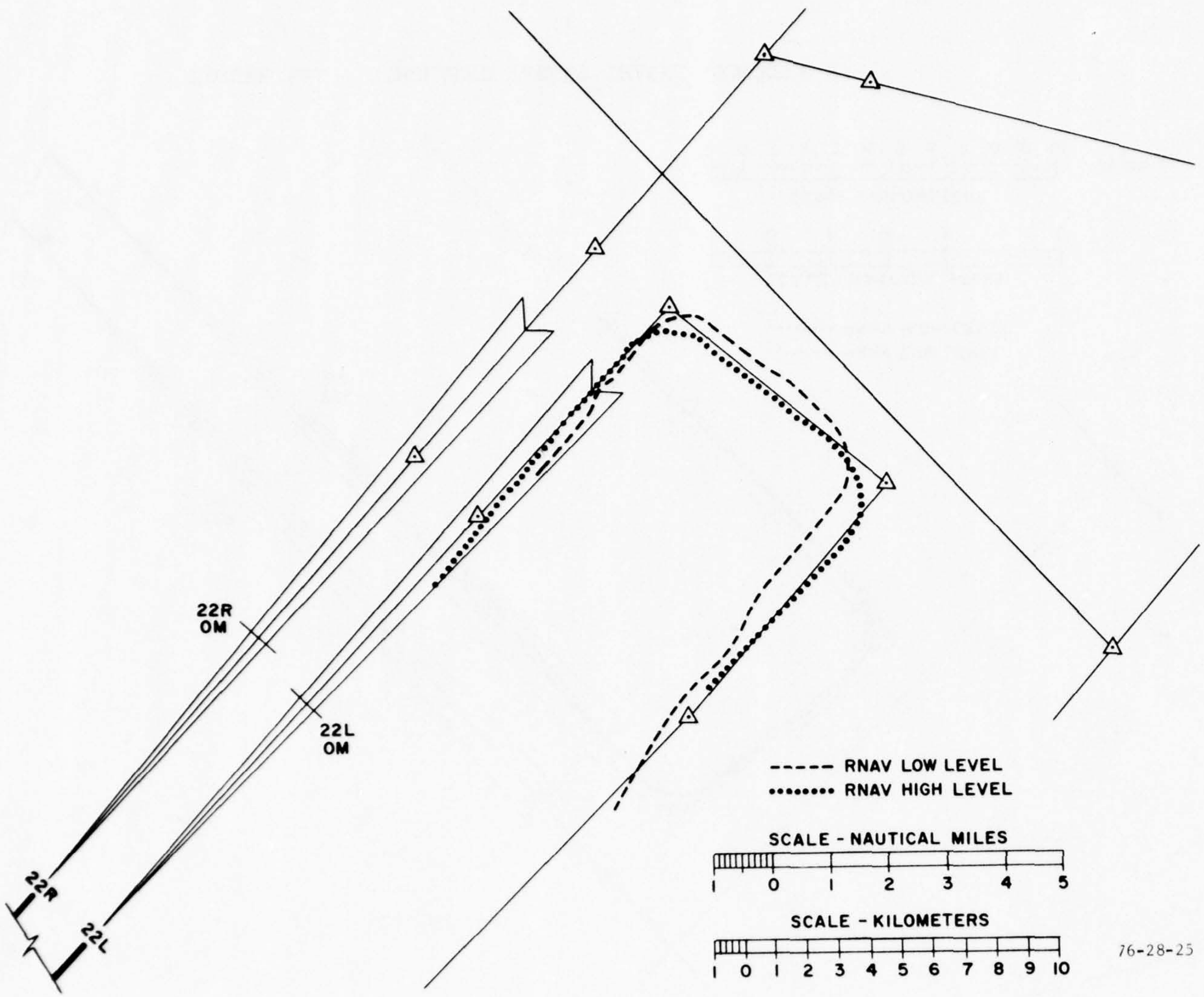


FIGURE 25. SIMULATED TARGET TRACKS (EXAMPLE 3)

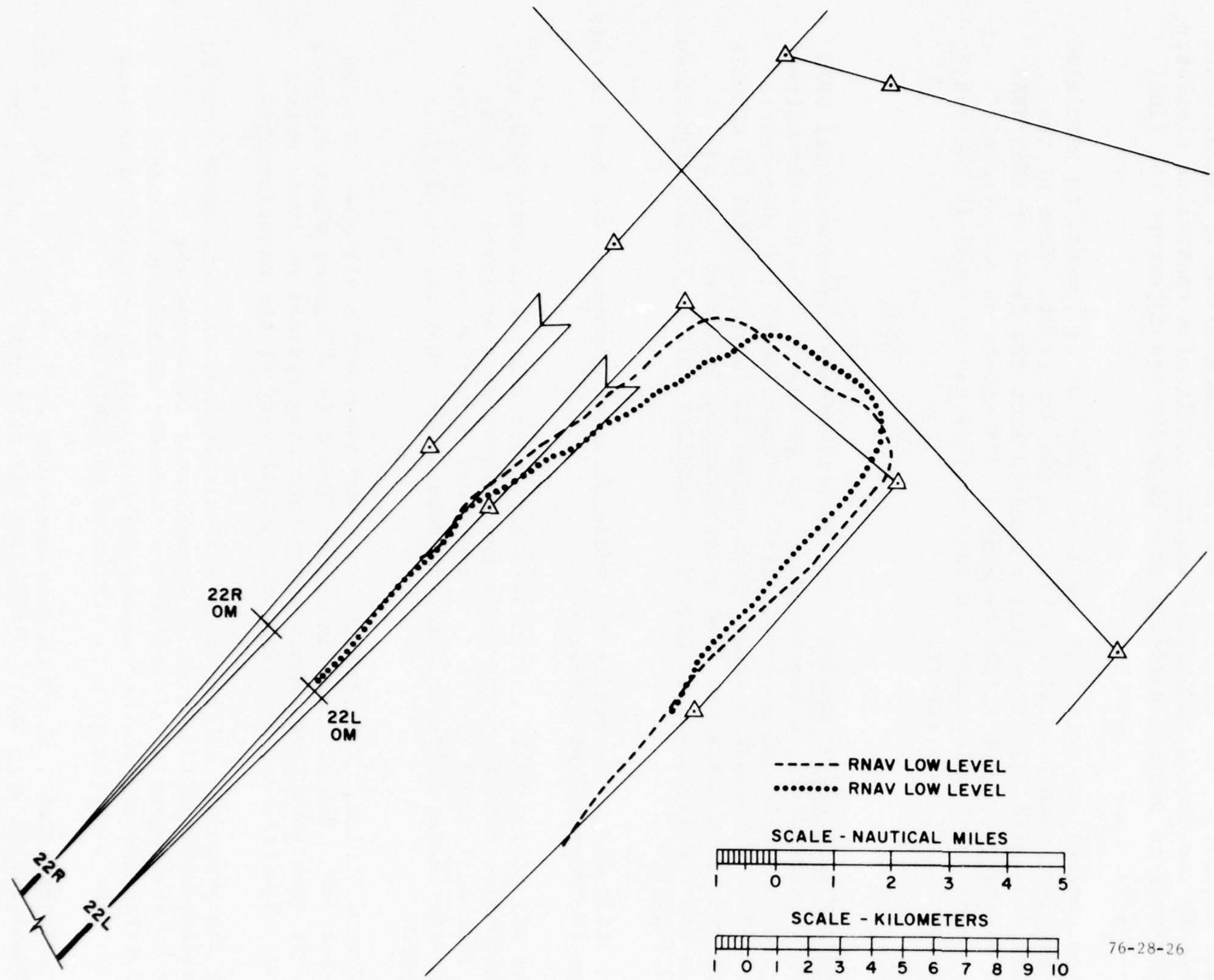


FIGURE 26. SIMULATED TARGET TRACKS (EXAMPLE 4)

avionics of the aircraft involved and the actions of the pilots utilizing the equipment. In this event, the turn to the base leg is the point of illustration where separation would have been most seriously affected by the performance of the avionics. The turn to the final approach course by the aircraft represented by the dotted flightpath was the result of a controller clearance for the aircraft to proceed directly to a waypoint and intercept the final approach course.

Most of the controllers felt that the lower level of equipment, as simulated, did pose problems when precision navigation was important. Some of the controllers indicated that they felt a need to know the level of RNAV/VNAV equipment employed by each flight because of its effect on the aircraft's performance. Additional information on this subject can be found in the subjective data portion of this report.

SUBJECTIVE DATA.

CONTROLLER ATTITUDE QUESTIONNAIRE. In the preliminary two-dimensional RNAV simulation (reference 2), a questionnaire was employed. The questionnaire was designed to sample and measure controller reaction to the introduction and use of RNAV in the ATC system. Item number 20 in the SUMMARY OF RESULTS section of reference 2 states: "The questionnaires indicated that as experience and familiarity were gained, controller opinion became significantly in favor of RNAV."

A similar attitude questionnaire and administration procedure was used in this study with two significant differences.

1. Since all of the NAFEC controllers had prior experience with RNAV, only the questionnaire data from the field controllers were analyzed. It was realized that this would result in a sample of only five controllers, thus requiring very large shifts in attitude toward RNAV/VNAV for statistical significance.

2. A "Forced Choice," True/False format was adopted for all questionnaire items except one. The elimination of the "Don't Know" choice which was used in the first questionnaires, while again requiring radical attitude shifts for statistical significance, increased the sensitivity of the questionnaire.

Following the procedure of the first RNAV simulation, the same questionnaire was administered three times; first, immediately following the initial briefing and prior to the beginning of controller training; second, at the conclusion of the training and exploratory phase; and third, at the completion of data collection. The questionnaire is presented in table 18.

Of the true/false questions, note that questions 2, 5, 9, 12, 14, 16, 19, and 20 deal specifically with VNAV. Since, in the data collection phase, the field controllers did not use the VNAV functions for the control of traffic, they have been eliminated from the data analysis.

TABLE 18. CONTROLLER QUESTIONNAIRE

You have now had several weeks of experience in handling simulated RNAV/VNAV-equipped aircraft. The attitudes that you had toward RNAV/VNAV a month ago may have changed. Please circle the "T" if you think each of the following statements is true, or the "F" if you think it is false. PLEASE BE SURE TO ANSWER ALL QUESTIONS.

1.	RNAV makes the controller's task more difficult.	T	F
2.	VNAV makes the controller's task more difficult.	T	F
3.	Mixtures of RNAV, VNAV, and radar-vectored aircraft make the controller's task more difficult.	T	F
4.	Some form of RNAV should be used by all commercial aircraft.	T	F
5.	Some form of VNAV should be used by all commercial aircraft.	T	F
6.	Mixtures of RNAV and radar-vectored aircraft will increase operations rates.	T	F
7.	Mixtures of RNAV, VNAV, and radar-vectored aircraft will increase operations rates.	T	F
8.	The use of RNAV will make the controller's job easier.	T	F
9.	The use of VNAV will make the controller's job easier.	T	F
10.	The simultaneous occurrence of RNAV, VNAV, and radar-vectored aircraft in the system will make the controller's job easier.	T	F
11.	RNAV should not be used in the terminal area.	T	F
12.	VNAV should not be used in the terminal area.	T	F
13.	RNAV is easy to learn to live with.	T	F
14.	VNAV is easy to learn to live with.	T	F
15.	RNAV will never work in the real world environment.	T	F
16.	VNAV will never work in the real world environment.	T	F
17.	With an RNAV and radar-vectored aircraft mix, a greater number of controllers will be required to move the same amount of traffic.	T	F
18.	With an VNAV/RNAV and radar-vectored traffic mix, a greater number of contollers will be required to move the same amount of traffic.	T	F
19.	Two-segment VNAV approaches and departures should not be used.	T	F
20.	Stacked arrivals and departures increased traffic handling capacity.	T	F

In light of your experience with RNAV in this simulation, circle the statement that most closely matches your opinion on whether RNAV should be put into operational usage.

-2	a.	I strongly oppose its use.
-1	b.	I oppose its use.
0	c.	I am indifferent to its use.
+1	d.	I favor its use.
+2	e.	I strongly favor its use.

TABLE 19. CONTROLLER ATTITUDE CHANGES TOWARD RNAV FROM FIRST TO SECOND ADMINISTRATION

	First Administration		Second Administration		Opinion Shifts		
Question	Favorable	Unfavorable	Favorable	Unfavorable	More Favorable	Same	Less Favorable
1	1	4	4	1	3	2	0
3	0	5	2	3	2	3	0
4	3	2	5	0	2	3	0
6	0	5	0	5	0	5	0
7	0	5	0	5	0	5	0
8	0	5	3	2	3	2	0
10	0	5	0	5	0	5	0
11	0	5	5	0	5	0	0
13	1	4	5	0	4	1	0
15	2	3	5	0	3	2	0
17	1	4	2	3	1	4	0
18	1	4	1	4	0	5	0
Total	9	51	32	28	23	37	0

Table 19 shows the favorable and unfavorable responses to RNAV as well as the number of attitude shifts of the five field controllers between the first and second administrations of the questionnaire. Because the sample size of controllers was only five, nonparametric statistics were applied. The sign test, as tabled in reference 9 (Siegel, "Non-Parametric Statistics"), is accurate to three decimal places. Since a 10-0 difference has a .001 probability of occurrence by chance, the observed 23-0 attitude shift is obviously significant.

It is further interesting to note that on two of the questions, there was a unanimous shift from unfavorable to favorable. These two questions were (1) RNAV should not be used in the terminal area, (2) RNAV is easy to learn to live with. The 5-0 shift is significant statistically at the .031 level using the sign test.

The last question was a general attitude question on a five-point scale from -2 to +2. Table 20 shows the numerical value of the attitude shift from the first to the second questionnaire.

TABLE 20. GENERAL ATTITUDE SHIFT--FIRST TO SECOND ADMINISTRATION

Subject	First Response	Shift	Second Response
1	-1	+1	0
2	0	+1	+1
3	-1	+2	+1
4	0	+1	+1
5	-1	+2	+1

Using the Wilcox on Matched Pairs Test (reference 9) yielded a confidence level of .031 that the differences were significant. The Walsh Test (reference 9) yielded a confidence level of .02.

No significant differences were found between the second and third administration of the questionnaires. All changes in attitude which were recorded between the second and third questionnaires, however, were in the direction of a more favorable attitude toward RNAV.

CONTROLLER/PILOT INTERVIEWS. Upon completion of their participation in the RNAV/VNAV simulation, the five field controllers were questioned at length concerning both RNAV/VNAV and the conduct of the NAFEC simulation. Objective data from the simulation were not available to the controllers at the time of the interviews. There follows a summary of the results of these interviews.

When asked about the total amount of training they felt might be required by controllers prior to becoming proficient in the use of RNAV/VNAV techniques, their answers ranged from 1 week to 3 months, with the mean somewhere around 2 weeks. They felt that 1 to 5 days would be sufficient for classroom

training, with the remainder devoted to simulation. Prior to the data collection phase of the simulation, the controllers had been exposed to about 32 hours of laboratory training. All stated that there were still some unexpected situations which occurred during data collection.

When asked if they provided priority handling to equipped aircraft, four of the controllers replied negatively. The fifth stated that he did in the DSF, but would not have done so in the real world. He said that he had given RNAV/VNAV aircraft more priority, because he felt they were more difficult to control.

Concerning the RNAV/VNAV functions and control messages, all controllers felt that the most useful was the offset followed by the direct-to-waypoint maneuver for the spacing and control of aircraft in the terminal area. As to the magnitude of the offsets used, none required less than 1 nor more than 5 nmi. They felt that the average offset they used ranged from 2 to 3 nmi.

On the subject of communications, all five controllers said that they thought they talked least when the participation level was at the 100-percent level. Some thought that the communications level was highest at the 0-percent-equipped level (all radar vector), while others felt that the intermediate mixed RNAV/VNAV radar-vector levels caused the highest communications activity.

Concerning the reasons why they took aircraft off of their RNAV/VNAV mode of operation, three of the controllers stated that it was either to increase the precision of control, or that no suitable RNAV maneuver existed for the immediate effect desired. The other two controllers said they only used vectors on RNAV/VNAV aircraft to overcome what they felt might have been shortcomings in the DSF software. Four of the controllers said that they returned "broken" aircraft to RNAV/VNAV 100 percent of the time, while the fifth controller stated he did so 80-90 percent of the time.

During this simulation, the data blocks of aircraft targets were modified to display either the letter "R" or "V" if the aircraft were RNAV or VNAV equipped. This letter would be flashed if the aircraft was taken off the mode of route navigation, and, in the case of VNAV aircraft, the altitude field was flashed whenever the vertical gradient was perturbed. All of the controllers felt that the "R" and "V" were required, and four of the five controllers found the flashing letter useful. No opinions were offered concerning the utility of flashing the altitude field.

Concerning the two different levels of aircraft performance caused by two sets of parameters in the error model, all of the controllers said that they were able to discern the difference between the "high" and "low" level equipment. Most felt that the lower level of equipment did pose problems when precision navigation was important. Two controllers thought it would be important to know the level of equipment if it was going to affect the performance of the target; the other three said it was not important.

Generally speaking, the controllers did not feel that they had more positive control over their traffic when the aircraft were equipped, but most said that their confidence level was adequate so long as they knew that they could revert to radar vectoring when necessary.

The remaining questions generally concerned the simulated environment and the controller displays. All of the controllers noted the differences between the displays used in the DSF and those to which they were accustomed. However, most were able to make a satisfactory adjustment. They felt that, on the whole, the route structure was good, the video mapping adequate, and the waypoint placement and names satisfactory. They further stated that they felt satisfaction with the simulation, but pointed out some areas of DSF target performance which they felt were not as realistic as they would have liked.

Together, the five field controllers prepared a comprehensive appraisal of the use of RNAV/VNAV in terminal area operations which appears as appendix C of this report.

At the conclusion of the simulation, GAT II pilots and NAFEC controllers were assembled together for a comprehensive discussion of the various aspects of operating and controlling RNAV/VNAV-equipped aircraft. For the most part, pilots and controllers agreed that RNAV could be utilized with success in the terminal area. They were satisfied with the route structure which was designed for the simulation. They felt that most of the procedures and phraseologies were satisfactory. Those instances where suggestions were put forth are noted below.

The charts with which the pilots were supplied depicted their arrival and departure routes and final approaches, including all waypoints. The pilots indicated that the charts should have differentiated between those waypoints which were required for the navigation of a route from those which were placed there to provide a means for the controller to modify the route (i.e., shortcut or path stretch). The pilots stated that they often found themselves tuning in and flying to intermediate waypoints unnecessarily. Obviously, this presented more of a problem for the single-waypoint King system than it did for the 20-waypoint EDO.

Along the same lines, there was a series of waypoints along each final approach course which allowed the controllers to shortcut an aircraft from the base leg to the final approach course when traffic conditions warranted. Controllers and pilots alike expressed that radar vectors would be easier to use. This was partly because of the additional cockpit workload, and partly because of the natural delay incurred in selecting a waypoint on the RNAV computer as opposed to initiating a radar-vectored course change.

The pilots indicated that the lack of automatic pilots in the GAT simulators made it difficult to respond to RNAV route changes as quickly as they should have. This deficiency made it difficult for them to anticipate turns as well as they felt that they should.

Controllers and pilots felt that there was only one item of phraseology with which they had any problems. The phrase used for next-leg offsets ("after 'fix,' fly 2 miles left offset") was confusing. They suggested that each terminal route segment be given a specific name, or that the standard pattern leg names be used, so that the phraseology could be changed to "offset base leg 2 miles left."

SUMMARY OF RESULTS

1. As the participation level of the RNAV/VNAV-equipped traffic present in the simulation increased to 100 percent, the following results, mainly of interest to the system user, were noted:

a. Arrival start-point delay (which may be regarded as holding delay) was reduced by up to 34 percent over all the arrival routes combined.

b. Departure start-point delay remained at a constant figure over all departure routes combined at all participation levels.

c. Arrival rates were increased by as much as 3.26 percent.

d. Departure rates were constant at all participation levels.

e. Arrival aircraft time in system and distance flown decreased by 6.3 and 3.1 percent, respectively, over all the arrival routes combined.

f. Departure aircraft time in system and distance flown remained constant at all participation levels, except that time in system increased by as much as 7.5 percent for those VNAV departures which flew fixed gradients.

g. The higher the participation level, the lower the percentage of RNAV/VNAV-equipped aircraft which were taken off their programmed flightpaths, except that the percentage of VNAV-equipped aircraft which were taken off their vertical gradients remained constant regardless of the participation level.

h. No statistically significant difference in fuel consumption could be found between RNAV/VNAV-equipped aircraft.

2. Those results which would have a bearing upon ATC procedures are:

a. The controllers were able to make extensive and effective use of the offset and direct-to-waypoint instructions, as substitutes for radar vectoring in the sequencing and spacing of aircraft.

b. The most frequent use of the next-leg offset function was to shorten or lengthen the downwind leg.

c. The controllers did not use the delay fan function as described by the RNAV task force.

d. No advantage could be found for an airspace design based on VNAV gradients or a "stacked" route structure.

e. A major disadvantage to an airspace structure based solely upon VNAV gradients is the complex separation criteria which must be applied whenever aircraft are taken off their established route or gradient.

3. The controllers' workload decreased, as the participation level of the RNAV/VNAV-equipped aircraft present in the system increased. At the 100-percent level, the decreases were:

a. The number of controller radio transmissions was reduced by 23 to 58 percent, depending on the control position considered, and by 36.1 percent for the terminal facility as a whole.

b. Radio talk time was reduced by 28 to 69 percent at the individual control positions and 42 percent for the facility as a whole.

c. Individual reductions in control instructions ranged from 31 to 74 percent, while those for the whole facility were reduced by 58 percent.

4. Those results which would affect avionics were:

a. The direct-to-waypoint and parallel offset functions were the most frequently used of those functions available to the controllers during this simulation.

b. The controllers did not use the delay fan at all during this simulation.

c. The RNAV/VNAV-equipped traffic did not respond as quickly or with as much precision to impromptu RNAV control instructions as did aircraft which were radar vectored.

d. The presence of lower level avionics equipment in the simulated aircraft population disturbed the spacing established by the controllers, requiring increased control efforts to reestablish and maintain the desired spacing.

e. The lack of turn anticipation in the lower level avionics equipment often reduced the navigational precision below the level considered acceptable to the controllers.

f. Controllers used offsets only in 1-nmi increments in a range of 1 to 5 nmi.

5. As a result of the experience gained during this simulation, the controllers and GAT II pilots formed the following opinions:

a. Radar vectors were preferable to impromptu RNAV maneuvers when an aircraft was in close proximity to the final approach course.

b. Equipped aircraft were taken off their RNAV/VNAV mode of operation mainly to increase the precision of control or when no suitable RNAV/VNAV maneuver existed for the immediate effect desired.

c. Some form of data block symbology is necessary to identify those aircraft which are RNAV/VNAV equipped.

d. Adequate controller and pilot training is a prerequisite to the successful use of RNAV/VNAV in the terminal area.

e. Controller opinion shifted significantly in favor of the use of RNAV/VNAV as fimiliarity and experience increased.

CONCLUSIONS

1. Effects upon the system user which can be expected from the use of RNAV/VNAV in a high-density terminal area are:

a. Reduced arrival delays.

b. No change in departure delays.

c. Increased arrival rates.

d. No change in departure rates.

e. Reductions in time in system and flight miles for arrival flights.

f. No change in time in system and flight miles for departure flights, except that those VNAV flights which fly fixed gradients will spend more time in the system than those which do not.

g. A reduction in pilot dependence upon radar vectoring for navigation in the terminal area.

2. The use of RNAV/VNAV in the terminal area can be expected to have the following effects upon ATC procedures:

a. Radar vectoring will be greatly reduced in favor of RNAV maneuvers.

b. The next-leg offset function will be useful for the shortening or lengthening of the downwind leg.

c. The delay fan will not be used extensively by the controllers.

d. Route structures based upon the most advantageous RNAV routings available will provide equal benefits to VNAV and radar-vectored aircraft.

e. Route structures and ATC procedures should not be based upon VNAV gradients due to the complex separation criteria which must be applied to those aircraft which are taken off their routes and/or gradients.

3. The following reductions in controller workload can be anticipated when RNAV is implemented in a busy terminal area:

a. Major decreases in radio transmissions.

b. Substantial reduction in radio talk time.

c. Over a 50-percent reduction in the number of control instructions.

4. To derive the maximum benefits from RNAV, the following characteristics are required of avionics systems which would be used in a high-density terminal area:

a. The ability to fly direct-to-waypoint and parallel offset maneuvers.

b. Delay fan function is not required unless needed by a computerized metering and spacing system.

c. The capability to respond as quickly and precisely to impromptu instructions as radar-vectored aircraft.

d. A level of accuracy similar to the higher level of avionics simulated.

e. Turn anticipation.

f. Offset range of 1 to 7 nmi in 1-nmi increments.

5. Based upon the opinions offered by the controllers and pilots, it is concluded that:

a. Radar vectors will still be utilized by the controllers whenever precision maneuvers are required near the final approach course.

b. RNAV/VNAV-equipped aircraft will be taken off their programmed flightpaths and radar vectored whenever no suitable RNAV/VNAV maneuver exists for the effect desired by the controller.

c. Data block symbology is required to identify RNAV/VNAV-equipped aircraft.

d. Controllers and pilots must be adequately trained in the use of RNAV for it to be effective in the terminal area.

e. Controller acceptance of RNAV will increase significantly with experience and familiarity with its use.

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APPENDIX A

ERROR MODEL

LIST OF ILLUSTRATIONS

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APPENDIX A

ERROR MODEL

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The RNAV navigational errors were divided into the following components: ground station, airborne equipment, and flight technical error. For those systems which did not have slant range correction, the slant range error was budgeted as part of the airborne equipment error component. The error components for RNAV/VNAV flights are summarized in table A-1.

TABLE A-1. RNAV/VNAV NAVIGATIONAL ERROR MODEL COMPONENTS

Error Components for RNAV/VNAV-Equipped Aircraft	Application
VOR Ground Station	Dynamic function of true azimuth
DME Ground Station	Constant bias for each station
VOR Airborne Equipment	Constant bias for each flight
DME Airborne Equipment	Constant bias for each flight
Slant Range	Function of altitude and ground range to station
Flight Technical	Includes turn anticipation effect and corrective manuevers
Speed	Random percentage of indicated airspeed
Vertical	Function of along-track error only

The different error components were assumed to be statistically independent: this assumption allowed the errors to be additive.

ERROR MODEL.

GROUND STATION ERROR. The ground station error perturbed the VOR/DME measurements used to estimate the aircraft's location. Actual bearing error reports collected by Flight Inspection Field Office (FIFO) were studied to establish the characteristics of the VOR error. In this investigation, several VOR facilities in the New York area were selected as representative ground stations.

The distance measuring equipment (DME) error was very small and was assumed to be constant. For this reason, no attempts were made to use field data in modeling this error component.

The pattern of the ground station VOR azimuth error varied slowly with respect to time: aircraft which flew overlapping bearings exhibited similar error patterns even when the flights were flown with a 1-month interlude. Over a period of a year, the patterns varied substantially. However, it was decided to keep the error patterns constant during the simulation.

It had been recommended that the VOR error component caused by the ground station could be modeled as a constant bias for different regions around the facility. Field data contradicted this assumption for a majority of the actual stations studied. This was especially true for the JFK VOR data. As illustrated in figure A-1, the error varied periodically as a function of the true azimuth. This implied that the error components must be updated almost continuously as an aircraft's true azimuth changed.

In order to model this pattern efficiently with respect to computer processing time, a table lookup technique was used. The error component of each azimuth was stored for all the stations; the truncated value of the true azimuth was used as the index to select the correct VOR error. Since only six VOR facilities were used in the experiment, the error pattern tables did not require a large amount of core storage.

Since the VOR error component was a dynamic function of the true azimuth (Θ), the error was computed each time the aircraft's position was updated. The ground station estimated azimuth, Θ_s, was defined by:

$$\Theta_s = \Theta + g(\mathrm{Int}(\Theta),k)$$

where $\mathrm{Int}(\Theta)$ is the integer truncated true azimuth; k is the ground station index; and, g (.,.) is the functional error values stored in tabular form. That is, the truncated true azimuth and the ground station index were used as pointers to select the VOR error from the function, g, stored as a table.

The ground station DME error was assumed to be a constant bias for each station. Each time an aircraft changed to a new ground station, a range error ($\Delta\rho_s$) which was selected from a truncated 2σ Gaussian distribution with zero mean was added to the true range. Therefore, each time an aircraft selected a new ground station, the true range (ρ) was offset by the DME error ($\Delta\rho_s$) to produce the estimated ground station DME measurement ρ_s where

$$\rho_s = \rho + \Delta\rho_s$$

<u>AIRBORNE EQUIPMENT ERROR</u>. Except for the RNAV computer error component, the airborne equipment error was combined to perturb the VOR/DME measurements used to calculate the aircraft's measured location. The airborne VOR equipment error ($\Delta\rho a$) and the airborne DME equipment error ($\Delta\theta a$) were assumed to be constant biases for each flight. The values of $\Delta\Theta_a$ and $\Delta\rho a$ were selected once for each flight. These variables were assumed to have truncated 2σ Gaussian distributions with zero means.

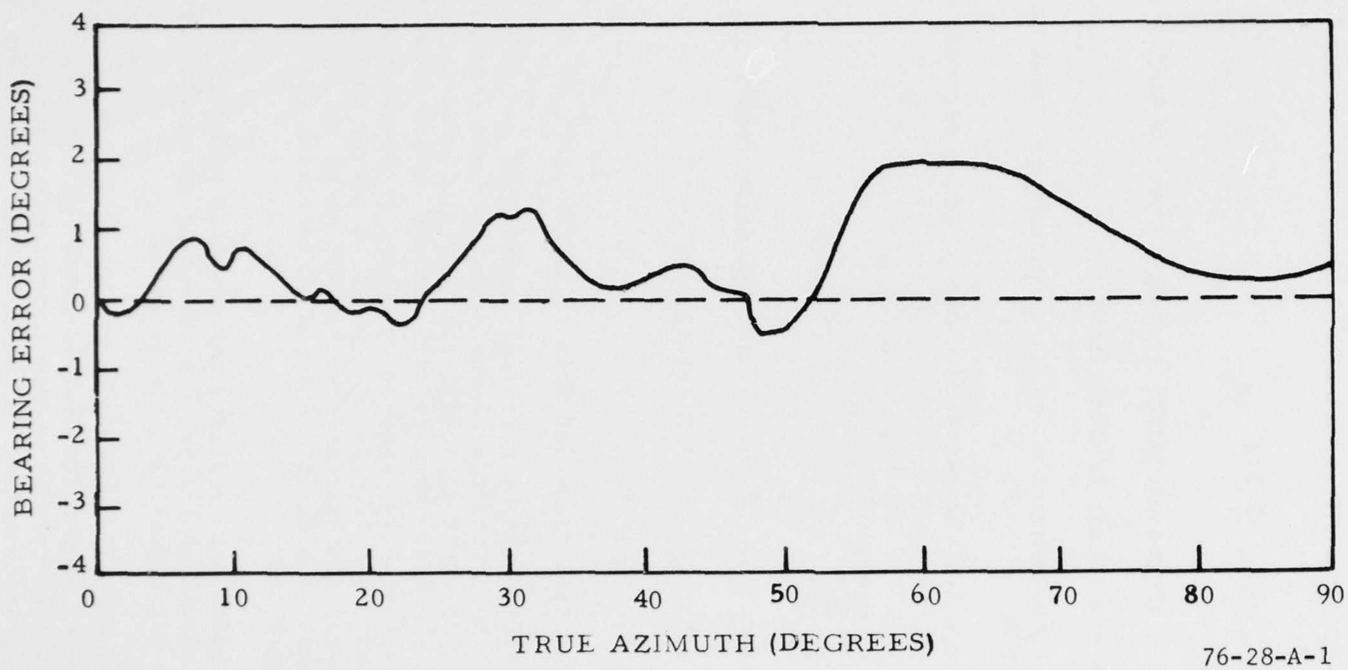

FIGURE A-1. BEARING ERROR REPORT, JFK VOR, NEW YORK

For those RNAV systems which did not have slant range correction, the slant range error was applied when the aircraft was close to the VORTAC (when the ratio of the altitude to the ground-projected distance was greater than 0.3). The slant range error $\Delta\rho_r$ only affected the range measurements and was computed by;

$$\Delta\rho_r = (d^2 + h^2)^{1/2} - d$$

where; d = ground-projected distance from the VORTAC to the aircraft

h = altitude of the aircraft

A common measure, such as nautical miles or kilometers, must be used for both distance and altitude.

The azimuth and range for the measured position of an aircraft were given by the following:

$$\rho_m = \rho_s + \Delta\rho_a + \Delta\rho_r$$

$$\rho_m = \rho_s + \Delta\rho_a$$

and substituting equations for the VOR and DME error components gave;

$$\rho_m = \quad + \quad \rho_a + \Delta\rho_r + g(\mathrm{Int}\ (\theta),\ k)$$

$$\Theta m = \Theta + \Delta\Theta_s + \Delta\Theta_a$$

where ρ,Θ were the actual range and azimuth to the aircraft.

FLIGHT TECHNICAL ERROR. Flight technical error (FTE) was defined to be the difference between the aircraft's measured position and the desired position on the true track. An event-type algorithm was developed to model the variation due to FTE in the DSF. When certain defined events occurred, either an aircraft crossing a threshold boundary or making a segment turn, the FTE algorithm controlled the corrective maneuvers to return the aircraft to the true track. The basic features of the RNAV FTE model are described in the following paragraphs. A schematic diagram illustrating the model parameters is included in figure A-2.

(1) The FTE model only utilized the measured position of the aircraft, not the actual position. The remaining paragraphs refer to measured position not actual aircraft location.

(2) When the measured position of the aircraft was outside of a "no-action zone" around the desired position, the program initiated a corrective maneuver to regain the correct track; i.e., the crosstrack error, e_c, was compared to the no-action zone threshold, t_c, to determine whether the aircraft was outside of the no-action zone.

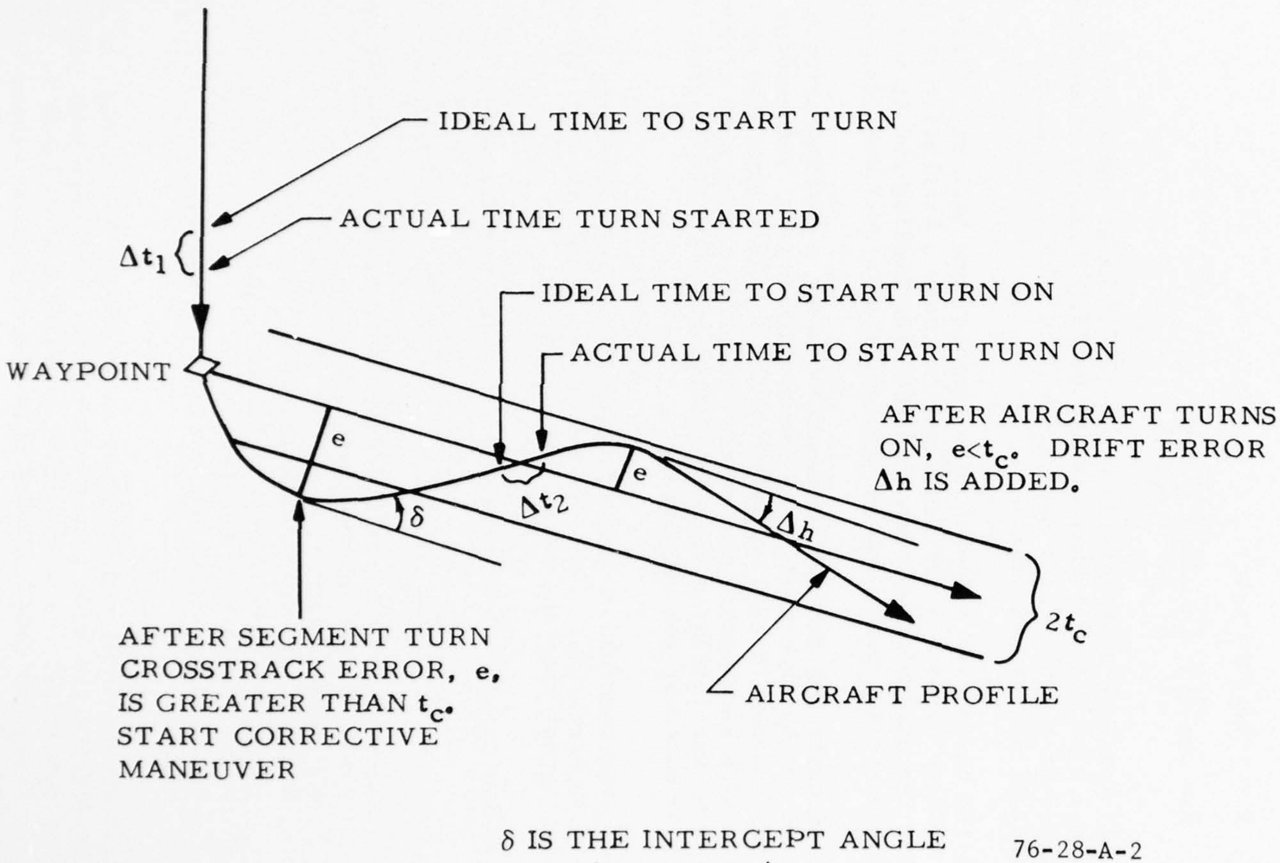

FIGURE A-2. SCHEMATIC DIAGRAM ILLUSTRATING RNAV FTE ALGORITHM

(3) For the corrective maneuver, the aircraft turned back at an intercept angle δ, which is a function of crosstrack error, e_c, and the turning radius, r. A one-half standard turn rate of 1.5° per second will be assumed, where:

$$r = \text{vel}/(\text{turn rate})$$

$$\delta = \cos^{-1}\left[1 - \left(\frac{2 - \sqrt{2}}{4}\right)\left(\frac{e_c}{r}\right)\right]$$

Typically for a velocity of 150 knots (277.8 km/h) and a crosstrack error, e_c, of 0.6 (1.111 km), δ would be 19.1°. For a crosstrack error, e_c, of 1.2 nmi (2.22 km), δ would be 27.2°. A maximum intercept of 45° was assumed.

(4) During the corrective maneuver, the time to turn back was offset by a random time error Δt_2 (2σ Gaussian) to cause a bracketing effect. If after the aircraft had turned on the true heading and it was outside the no-action zone, another corrective maneuver was instigated.

(5) If the aircraft was inside the no-action zone, a heading error, Δ h, was added to the true heading to incorporate drift. The heading error was assumed to be a Gaussian random variable truncated at the 2σ value with zero mean. The heading error was added each time a new heading was initiated, either after a segment turn or after a corrective maneuver was completed.

(6) To model over/undershoots during segment turns, a time-to-turn error, Δt_1, was incorporated. This was also a truncated Gaussian random variable, except that the mean can be nonzero.

In summary, the following parameters were specified for the FTE model:

PARAMETER	DESCRIPTION	UNITS
t_c	No-action threshold boundary	Nautical Miles/Kilometers
$E(\Delta t_1), \sigma(\Delta t_1)$	Mean and standard deviation of the segment time to run	Seconds
$E(\Delta t_2), \sigma(\Delta t_2)$	Mean and standard deviation of the corrective maneuver time to turn back to true heading	Seconds
$\sigma(\Delta h)$	Standard deviation of heading errors	Radians

A fast-time simulation was developed to study the proposed FTE model. As the initial step in validating the model, several computer runs were made under different parameter conditions. The resultant profiles are included in figures A-3, A-4, and A-5. These profiles included only the variations caused by FTE. The shape of these plots was very similar to data measured in the field for two types of equipment and data recorded on the GAT II simulators. These plots are included only to demonstrate the validity of the model, not to specify the parameter values.

$\bar{e} = -0.098$ nmi (0.182 km)

$s_e^2 = 0.091\ (\text{nmi})^2$ (0.169 km)

$t_c = 0.6$ nmi (1.111 km)

$E(\Delta t_1) = 10$ seconds

$\sigma_{\Delta t1} = 5$ seconds

$E(\Delta t_2) = 0$ seconds

$\sigma_{\Delta t2} = 5$ seconds

$\sigma_{\Delta h} = 2°$

± 1.5 nmi brackets (2.578 km)

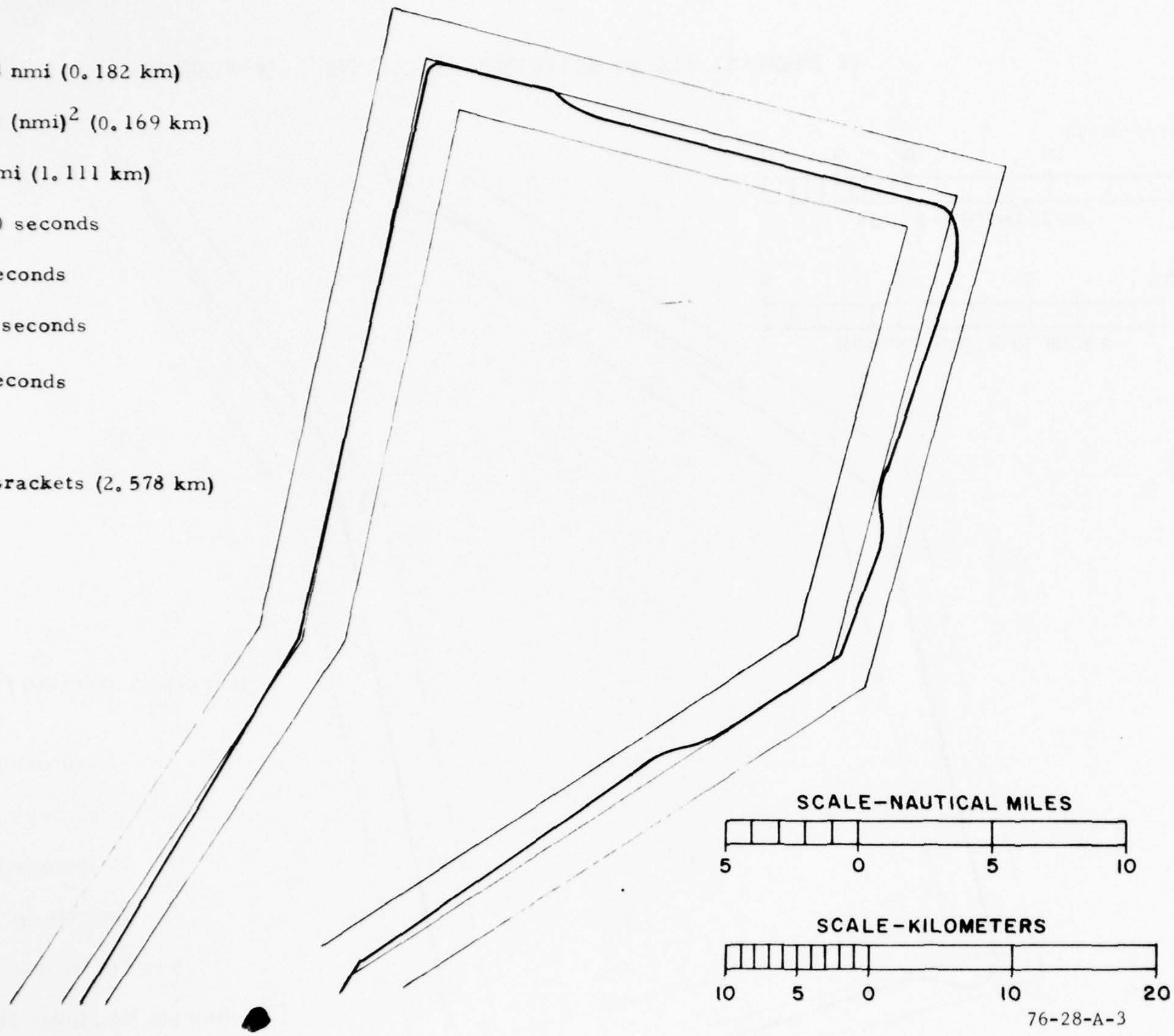

FIGURE A-3. FAST TIME SIMULATION OF FTE (EXAMPLE 1)

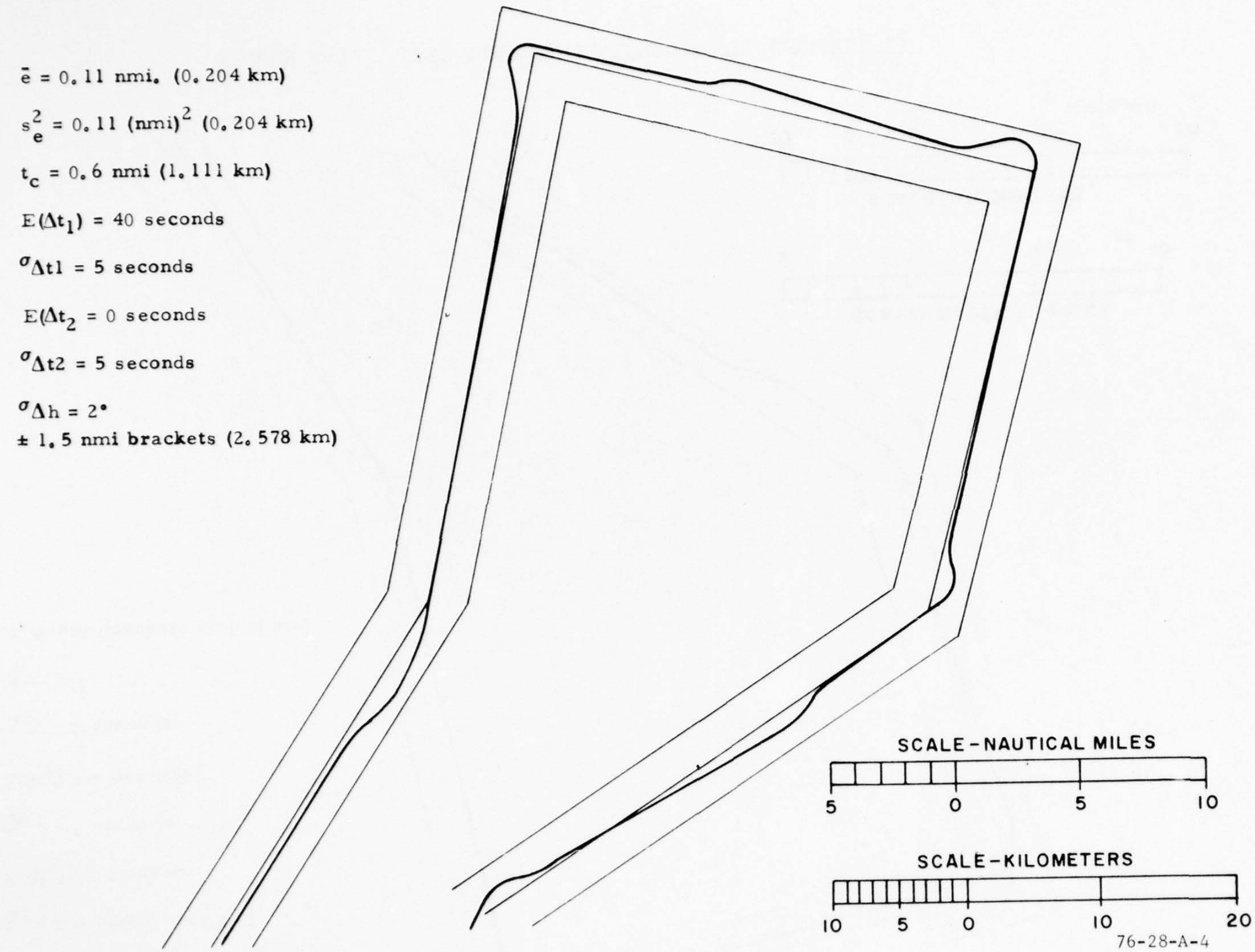

FIGURE A-4. FAST TIME SIMULATION OF FTE (EXAMPLE 2)

$\bar{e}$ = 0.85 nmi (1.594 km)

s_e^2 = 0.227 (nmi)^2 (0.42 km)

t_c = 0.6 nmi (1.111 km)

$E(\Delta t_1)$ = 40 seconds

$\sigma_{\Delta t1}$ = 5 seconds

$E(\Delta t_2)$ = 0 seconds

$\sigma_{\Delta t2}$ = 5 seconds

$\sigma_{\Delta h}$ = 5°

± 1.5 nmi brackets (2.578 km)

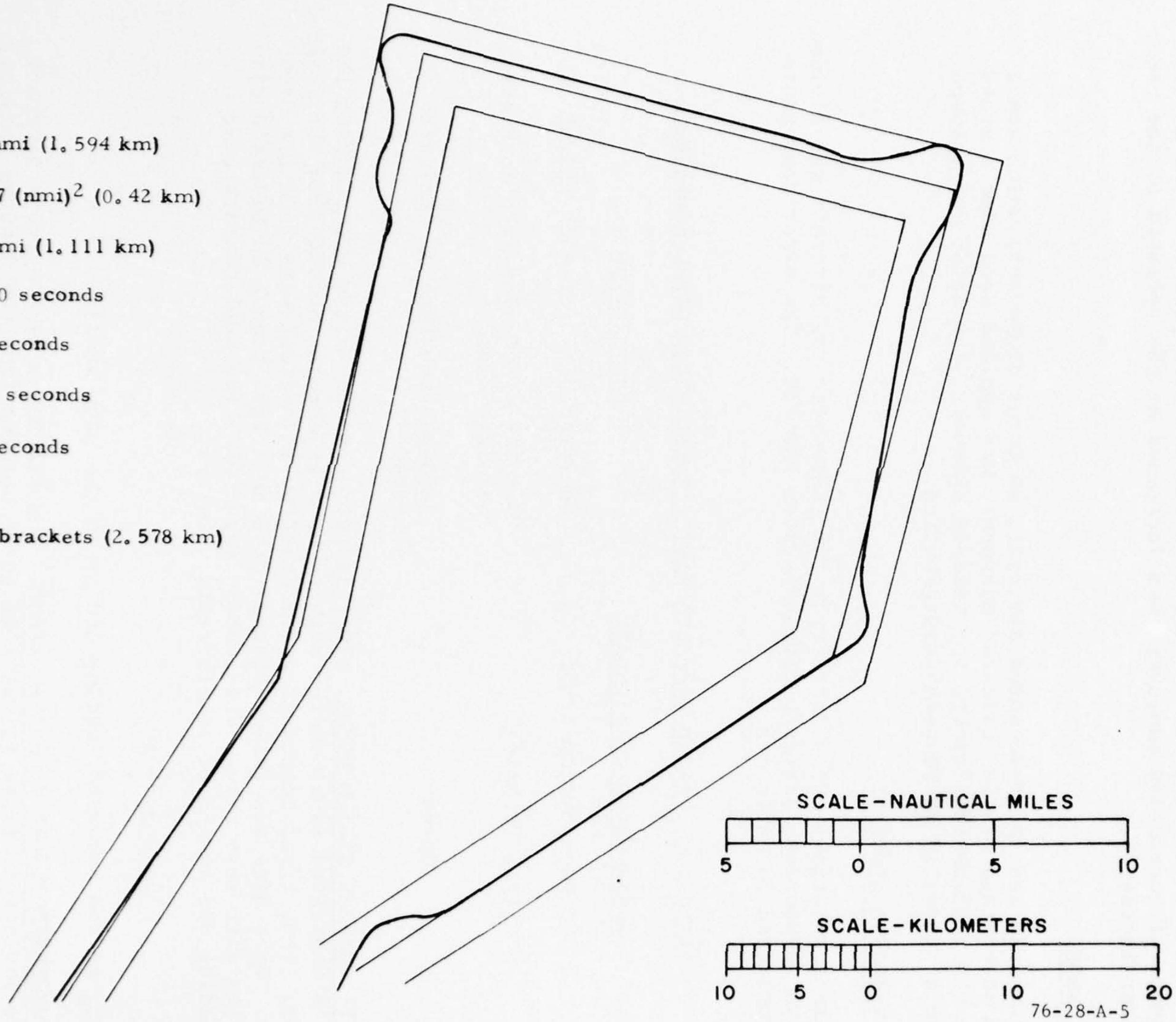

FIGURE A-5. FAST TIME SIMULATION OF FTE (EXAMPLE 3)

As illustrated in figures A-3 through A-5, the different characteristics of the FTE vary as a function of the parameters. The tendency and magnitude of turn overshoots increased as the expected time-to-turn parameter was increased. The number of corrective maneuvers was increased as the variance of the bearing error increases.

SPEED ERROR.

For both RNAV and radar-vectored aircraft, an error component, which was a random percentage of the indicated airspeed, was applied each time a speed change was implemented (except for takeoff speeds). The error was assumed to have a truncated 2σ Gaussian distribution.

RADAR-VECTORED AIRCRAFT.

For this simulation, the flight error for radar-vectored aircraft was divided into two categories, aircraft compass system and FTE. The error components are summarized in table A-2.

TABLE A-2. RADAR-VECTORED NAVIGATIONAL ERROR MODEL COMPONENTS

Radar-Vectored Aircraft	Description
Compass System Error	Constant bias for each flight
Flight Technical	Heading error added for each new heading issued
Speed	Random Percentage of indicated airspeed

AIRCRAFT COMPASS SYSTEM ERROR. The aircraft compass system error caused the flight's indicated radar vector path to have an angular offset from the desired heading. This error component was modeled by a constant bias (ΔC) for each flight. This bias was selected once for each flight from a 2σ Gaussian distribution with zero mean. The compass error (ΔC) was applied each time a new heading was issued to an aircraft. That is,

$$\beta_m = \beta_t + \Delta C$$

where β_m is the measured heading and β_t is the true heading.

RADAR-VECTORED FLIGHT TECHNICAL ERROR. The FTE for radar-vectored aircraft was the deviation of the flight's measured heading from the desired heading. Since the vectored pilot has no means of determining the aircraft's deviation from the true track, the only corrective procedures possible are bearing adjustments. No data were available to model the frequency with which pilots make heading corrections. However, since the distances the aircraft flew in

this experiment were comparatively short, a heading error (ΔBf) was added each time a new heading was issued. Therefore, the heading which the aircraft followed is given by;

$$\beta = \beta_t + \Delta C + \Delta\beta_f$$

where ΔC is the compass system error and β_t is the true heading desired. The heading error ($\Delta\beta_f$) will be selected from a truncated 2-Gaussian distribution. The time required for the DSF pilots to enter a new heading is assumed to approximate the actual delay to start turning an aircraft. For this reason, no provision for overshoot is included in the FTE algorithm for radar-vectored aircraft. Overshoots will result from the delay between the time the DSF pilots hear the new heading and the time they enter the command on their display.

APPENDIX B

2D/3D RNAV TERMINAL AREA DESIGN FOR NEW YORK--SOUTHWEST FLOW

LIST OF ILLUSTRATIONS

APPENDIX B

2D/3D RNAV TERMINAL AREA DESIGN FOR NEW YORK--SOUTHWEST FLOW FROM "TERMINAL AREA DESIGN ANALYSIS AND VALIDATION OF RNAV TASK FORCE CONCEPTS," FAA-RD-76-194

by E.D. McConkey
Champlain Technology Inc.

INTRODUCTION

BACKGROUND.

This report describes the design techniques and results of a task in which a two-dimensional/three-dimensional (2D/3D) RNAV terminal area design for the southwest flow at New York was developed. As a basis for beginning the 2D/3D design, the 1982 2D RNAV design for New York--Southwest Flow (82-01-01)--as reported in reference 1 and the 3D RNAV design for New York reported in reference 2 were used. In addition, qualitative assessments of the 1972 and 1977 New York designs that were simulated at the Digital Simulation Facility at NAFEC were obtained, and those items which pertained to the 1982 New York 2D design were given consideration in the combination 2D/3D design effort.

DESIGN TECHNIQUE.

As with the design effort described in reference 2, the 2D/3D RNAV design began with a horizontal projection of all of the New York terminal area routes on a map of the New York area. Routes were developed for the three major New York airports, John F. Kennedy, Laguardia, and Newark. All aircraft using the terminal were assumed to be 2D- or 3D-RNAV-equipped so navigation facility location constraints were minimal. Some holding airspace at the feeder fixes was considered in the design to accommodate up to three or four aircraft at altitudes comparable to the altitude that the aircraft nominally crosses the feeder fix.

Aircraft departing the terminal area were given separate departure routes depending upon whether they were 2D or 3D RNAV equipped. This was considered desirable in order to avoid aircraft conflicts at the periphery of the terminal area. Often the 3D routes are shorter than the 2D routes. Consequently, a 3D aircraft departure following a 2D aircraft departure off the runway with adequate separation could later conflict if the two aircraft exited the terminal at the same point, because the 3D aircraft would climb at a steeper gradient on a shorter route. This use of multiple departure points will have a significant affect upon the center sector that adjoins the terminal area. The terminal-to-enroute interface problem exceeded the scope of this design effort, however.

A lateral route separation of 1.5 nmi was used throughout the terminal area. This separation criterion was taken from reference 3 for 1977 and 1982 time periods. Vertical separation for the 3D routes was obtained from reference 4.

Gradients for the 3D routes were based upon the performance characteristics of several aircraft types under varying conditions. The descent gradient for each aircraft was nearly a constant at 300 feet/mile. Consequently, this value was used for descents from all altitudes for all aircraft types. The climb profiles varied widely, depending on aircraft type, ambient temperature, aircraft weight, and climb airspeed. Several typical profiles are shown in figure B-1. It can be seen that several of the profiles are quite similar. For example, the medium-weight DC9 (90,000 pounds) and the medium-weight B727 (140,000 pounds) have very similar low-speed climb profiles at standard temperatures. The heavy DC9 (100,000 pounds) and the heavy B727 (170,000 pounds) also have similar low-speed climb profiles at ISA+20° temperatures. Finally, a heavy B727 (170,000 pounds) climbs slightly better than heavy B747 (767,000 pounds) under high-temperature and high-airspeed conditions. As a consequence, three separate vertical gradients were selected for the 3D profiles. These gradients were based upon the gradients achieved for each type of aircraft at three altitude levels--10,000 feet, 18,000 feet, and 25,000 feet. The following is an index of aircraft used in the gradient analysis.

Profile Number	Type	Weight (pounds)	Temperature Conditions	Speed Profile
1	B727-100	140,000	ISA	Low-speed climb
2	DC9-30	90,000	ISA	Low-speed climb
3	DC9-30	100,000	ISA+20° C	Low-speed climb
4	DC9-30	100,000	ISA	High-speed climb
5	B727-100	170,000	ISA	High-speed climb
6	B727-100	170,000	ISA+20° C	Low-speed climb
7	B747B	750,000	ISA+15° C	High-speed climb

(Note: The 250-knots IAS limit was observed up to 10,000 feet)

High-Performance Profile

Aircraft Number	Altitude (ft)	Climb Rate (ft/nmi)	Composite (ft/nmi)
1	10,000	565	550
2	10,000	592	(5.18°)
1	18,000	347	350
2	18,000	344	(3.30°)
1	25,000	220	200
2	25,000	215	(1.89°)

Medium-Performance Profile

Aircraft Number	Altitude (ft)	Climb Rate (ft/nmi)	Composite (ft/nmi)
3	10,000	391	500
4	10,000	509	(3.77°)
5	10,000	416	
6	10,000	311	

3	18,000	184	200
4	18,000	233	(1.89°)
5	18,000	188	
6	18,000	167	
3	25,000	83	100
4	25,000	144	(0.94°)
5	25,000	87	
6	25,000	78	

Low-Performance Profile

6	10,000	311	300
7	10,000	267	(2.83°)
6	18,000	167	150
7	18,000	124	(1.41°)
6	25,000	78	100
7	25,000	96	(0.94°)

Design Results

The horizontal projection of the 2D and 3D routes for New York are shown in figure B-2. The routes may be identified as follows:

J-John F. Kennedy International	200 series--2D arrivals
L-LaGuardia	300 series--2D departures
E-Newark	500 series--3D departures

Aircraft 1 and 2 were selected for the high-performance profile, 3-6 were selected for the medium-performance profile and 6 and 7 were used for the low-performance profile. The results are as follows:

The routes are set up to apply generally to the octant concept as depicted in reference 3. Due to the multiple-airport situation, this concept is modified slightly in the southwest corner of the terminal area. Parallel departure routes are set up everywhere possible in order to facilitate traffic flow and make maximum use of the available airspace. Arrivals converge at the feeder fixes, and traffic is assumed to flow in trail from the feeder fix to the runway. The major benefits to the 3D users occur for the medium- and high-performance profiles whereby aircraft can be turned toward the departure point at the periphery of the terminal area sooner than the 2D aircraft and the low-performance 3D aircraft. In fact the 3D low-performance profile followed along the same route as the 2D aircraft in most cases. Consequently, there seems to be little advantage for the aircraft on a low-performancce 3D profile over that of the 2D aircraft. For the high- and medium-performance 3D departure profiles, considerable distance and altitude benefits can be obtained in several routes.

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AREA NAVIGATION/VERTICAL AREA NAVIGATION TERMINAL SIMULATION.(U)
MAR 77 W CRIMBRING, J MAURER
UNCLASSIFIED FAA-NA-76-28 FAA-RD-76-211 NL

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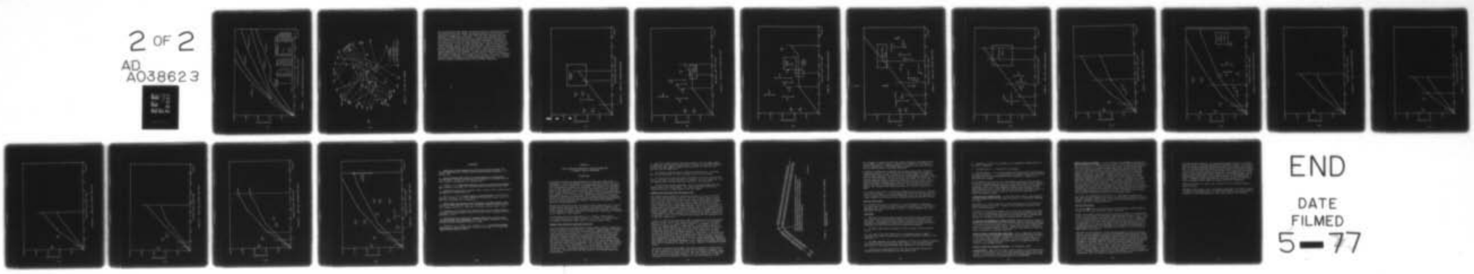

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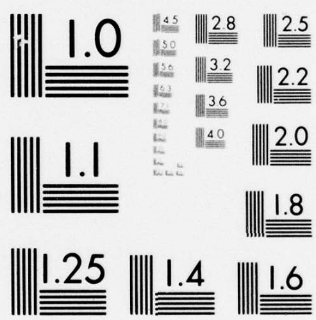
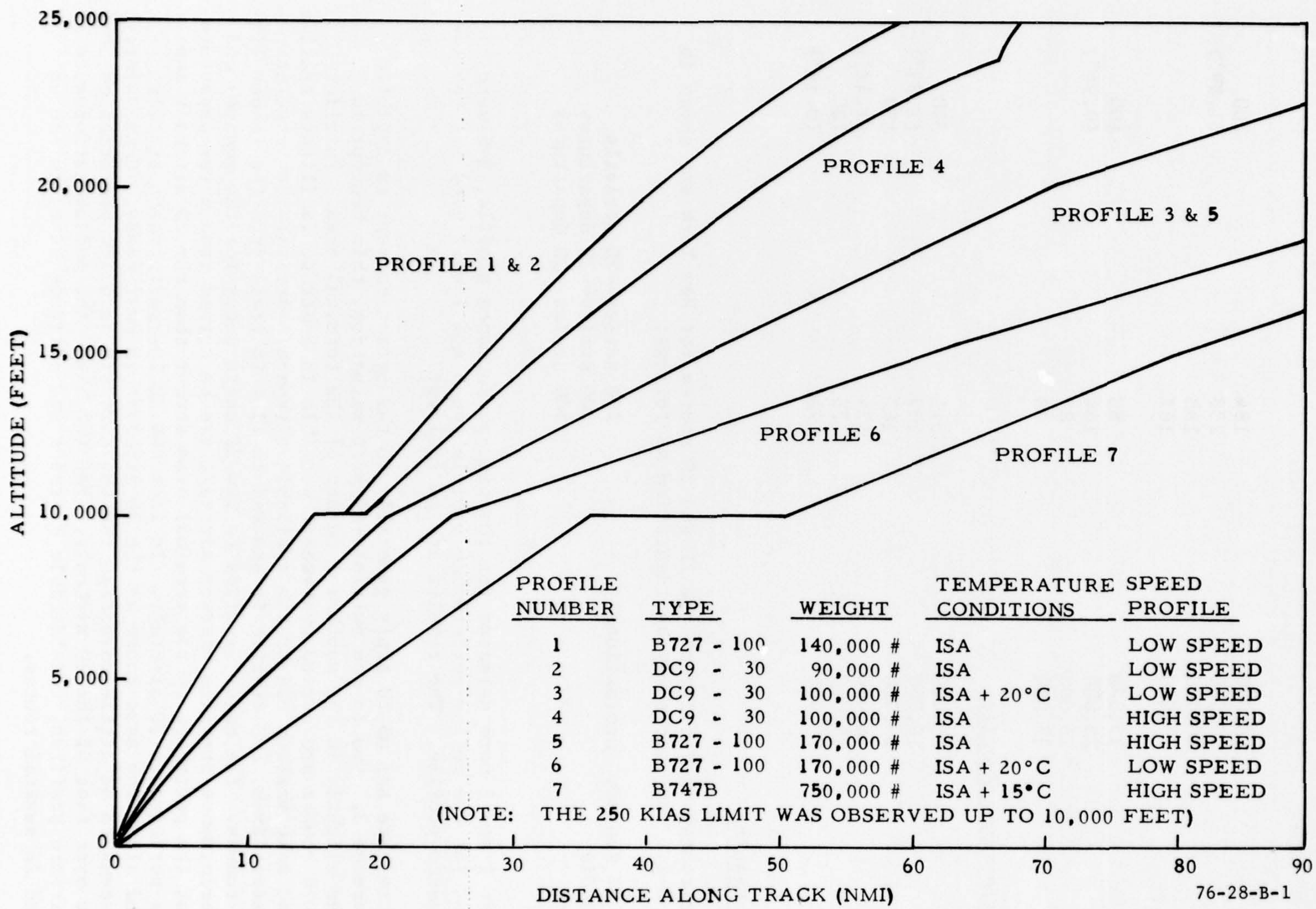


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



PROFILE NUMBER	TYPE	WEIGHT	TEMPERATURE CONDITIONS	SPEED PROFILE
1	B727 - 100	140,000 #	ISA	LOW SPEED
2	DC9 - 30	90,000 #	ISA	LOW SPEED
3	DC9 - 30	100,000 #	ISA + 20°C	LOW SPEED
4	DC9 - 30	100,000 #	ISA	HIGH SPEED
5	B727 - 100	170,000 #	ISA	HIGH SPEED
6	B727 - 100	170,000 #	ISA + 20°C	LOW SPEED
7	B747B	750,000 #	ISA + 15°C	HIGH SPEED

(NOTE: THE 250 KIAS LIMIT WAS OBSERVED UP TO 10,000 FEET)

FIGURE B-1. TYPICAL AIRCRAFT DISTANCE-ALTITUDE PROFILES

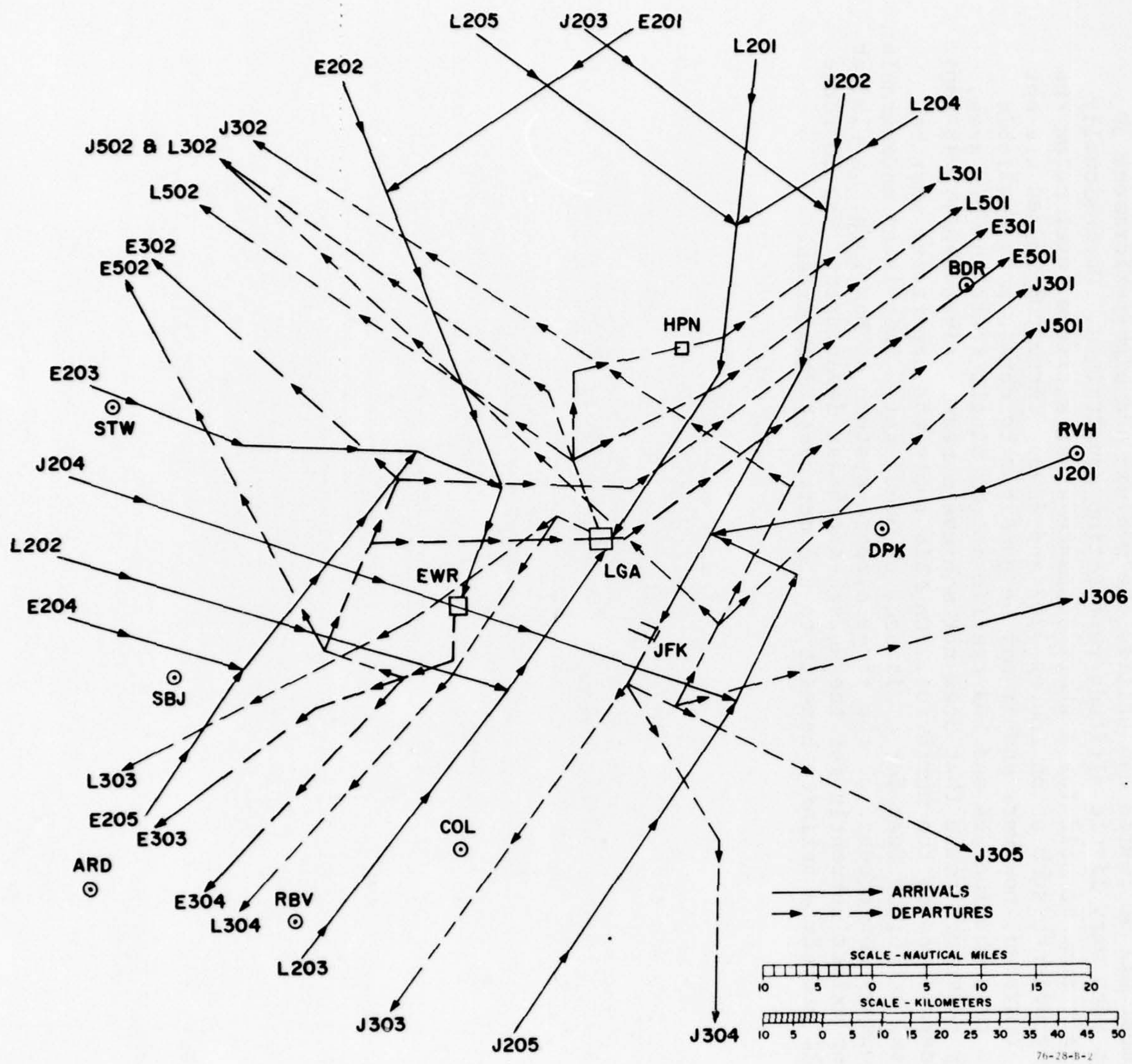


FIGURE B-2. NEW YORK 2D-3D TERMINAL

From the horizontal-route design, the vertical profile is obtained by plotting the altitude of the route versus the distance along the route as shown in figures B-3 through B-15. Route turn points and route crossing points are identified in these vertical profiles. It can be seen from these profiles that almost all 3D routes can utilize the medium- and high-performance 3D profiles with very little altitude restriction constraints. Occassionally an aircraft must be held for a short distance at an altitude level below the desired gradient, such as on routes J202 and J203. These two routes are not heavily traveled, however, and it may be possible to obtain more desirable profiles by combining JFK and LGA traffic into a single route in this area. The only departure route that does not achieve a near desired profile is E301-Newark departures to the northwest. On this route the departures must be held level at 10,000 feet for a distance of 30-35 nmi. This is an undesirable, but necessary consequence of the three airport systems at New York. A similar situation exists currently for the Newark-Northeast departures. The 3D route E501 will provide a definite benefit to the northeast departures.

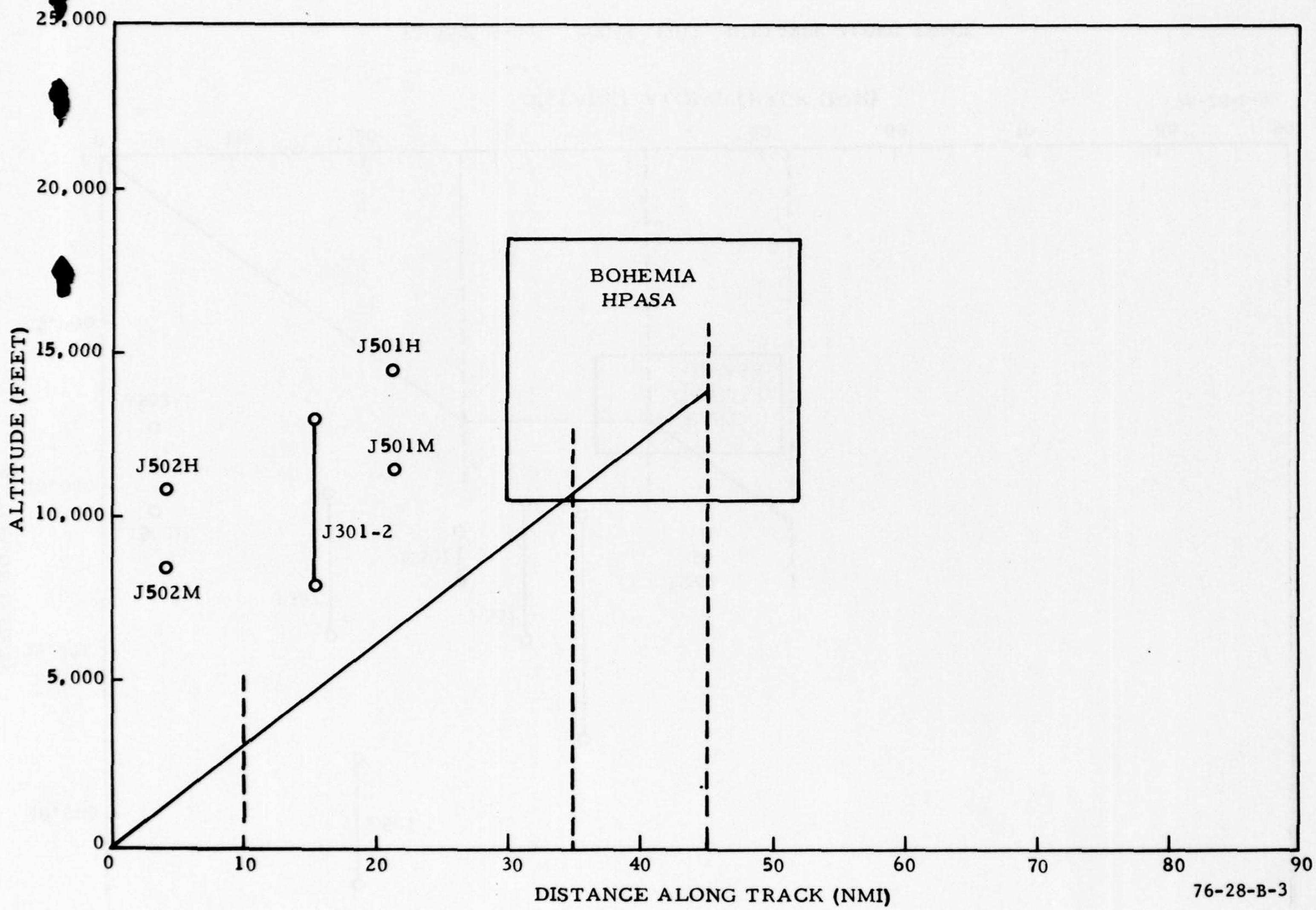


FIGURE B-3. ROUTE J201, DISTANCE ALONG TRACK

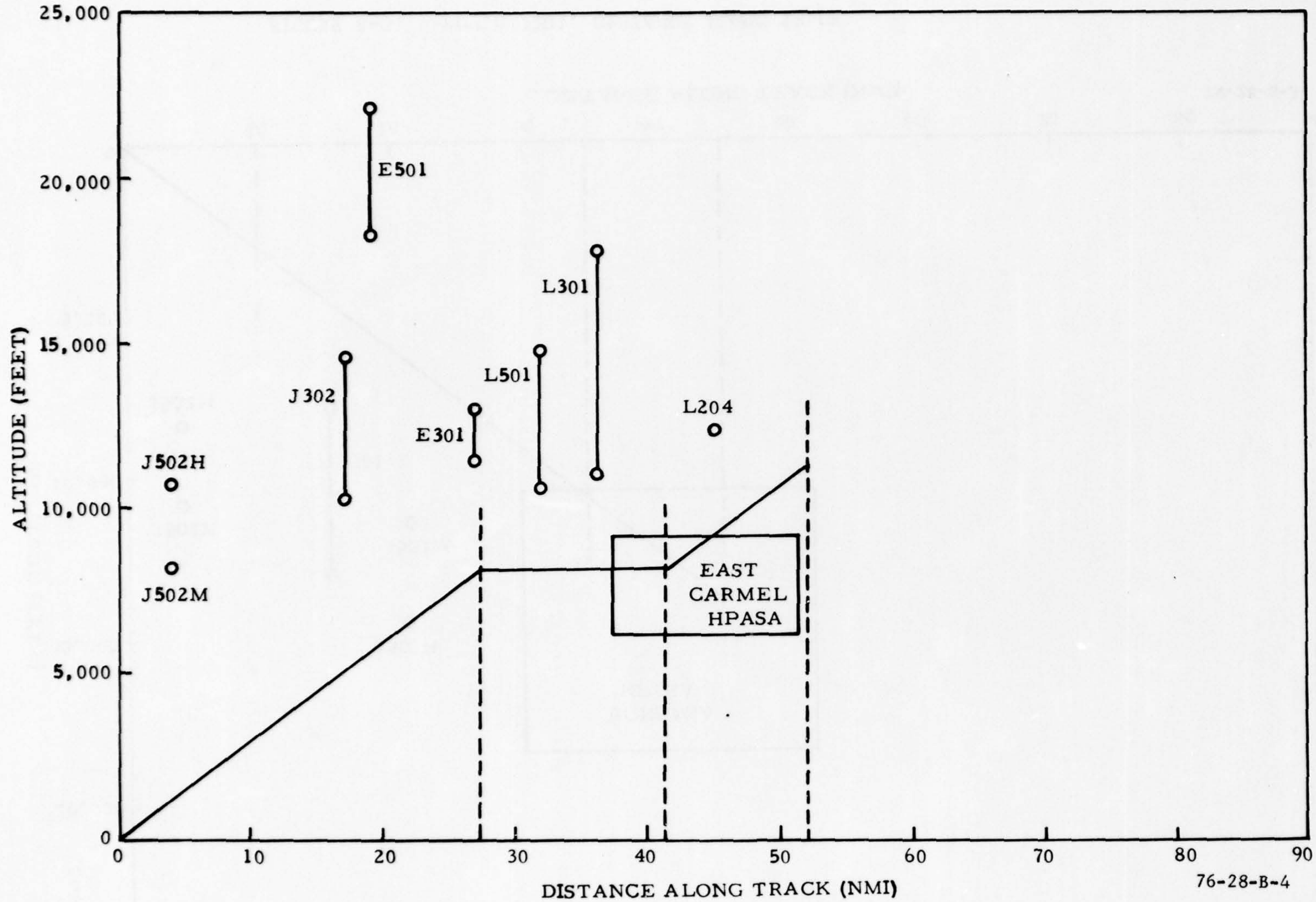


FIGURE B-4. ROUTE J202, DISTANCE ALONG TRACK

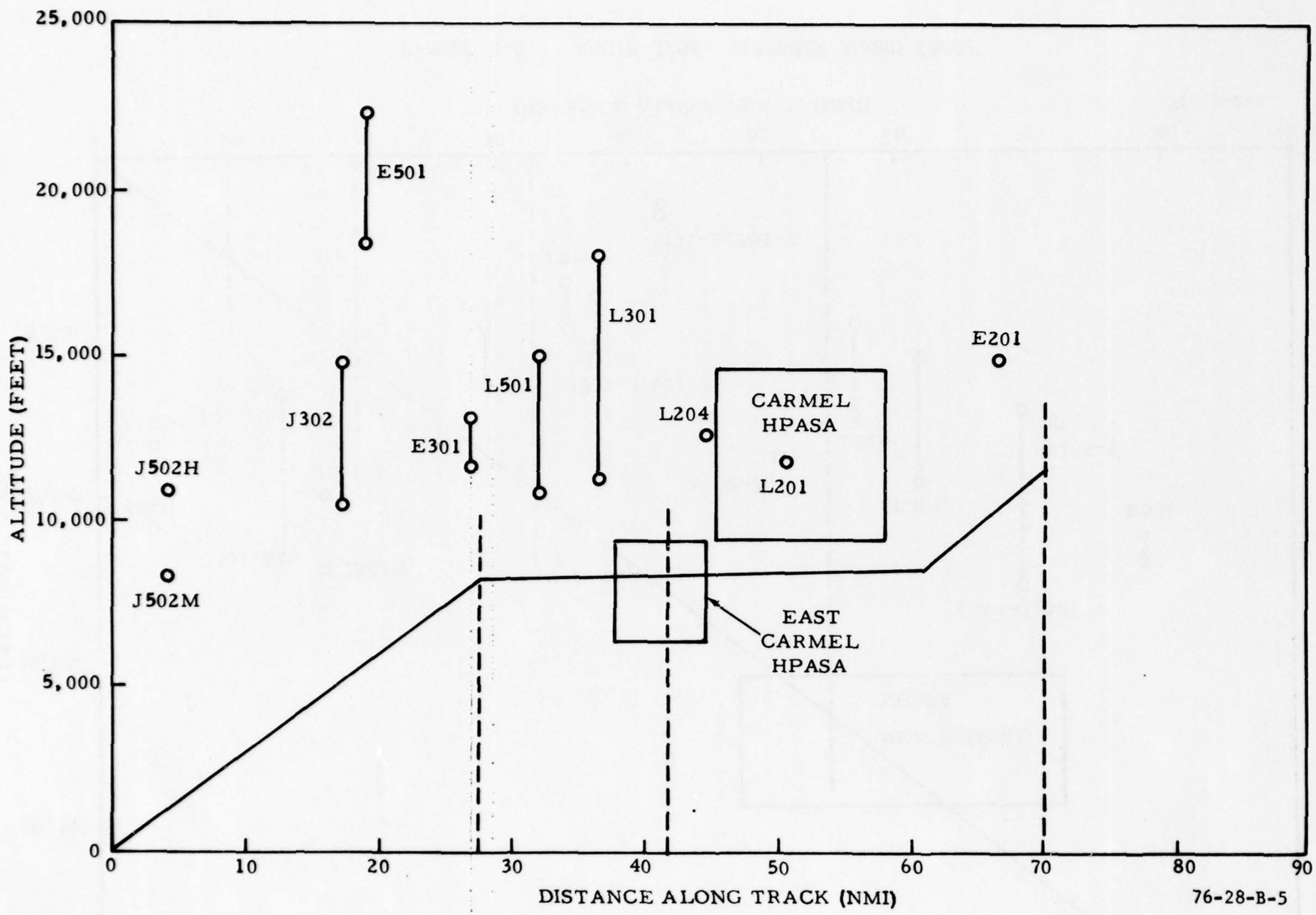


FIGURE B-5. ROUTE J203, DISTANCE ALONG TRACK

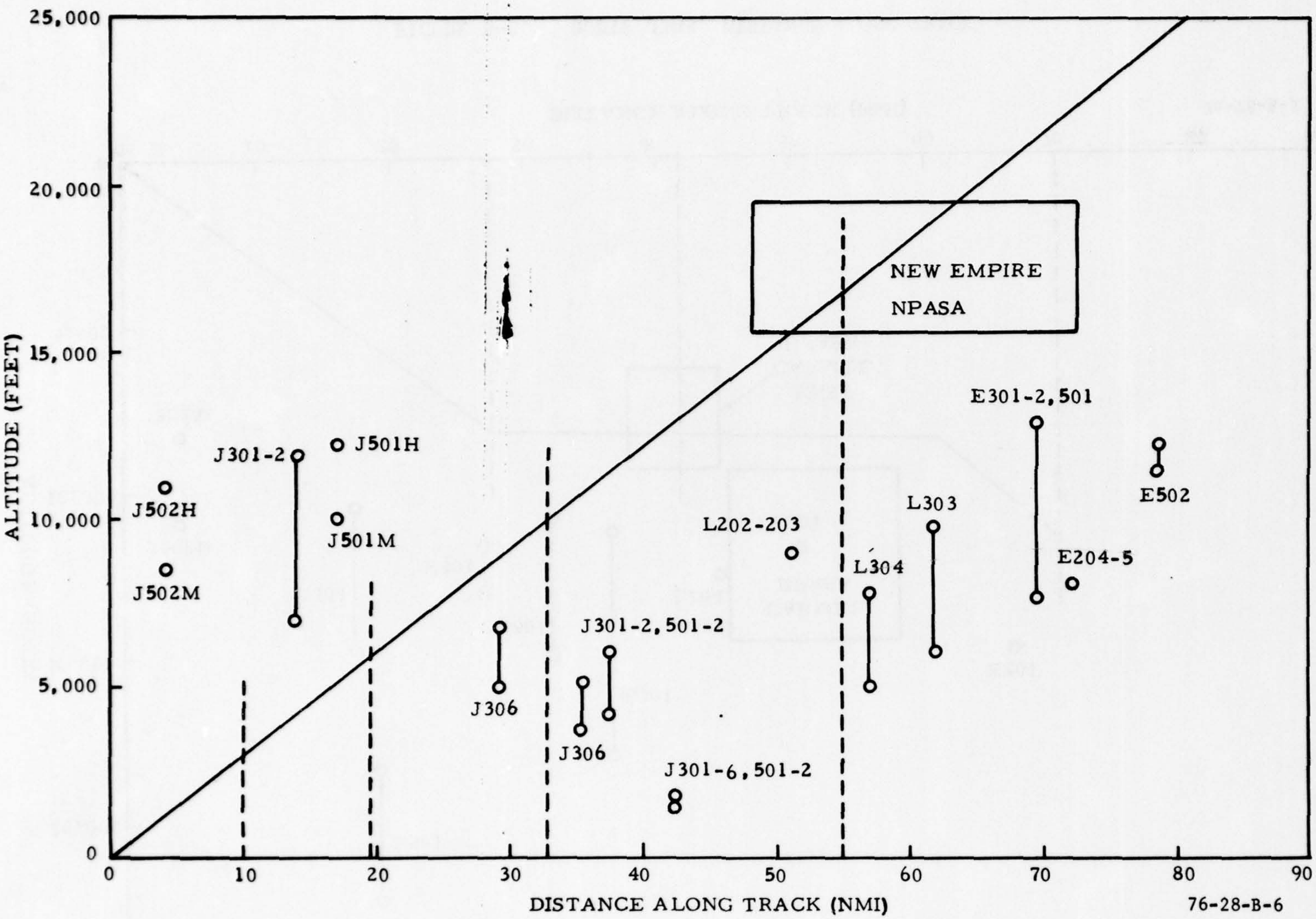


FIGURE B-6. ROUTE J204, DISTANCE ALONG TRACK

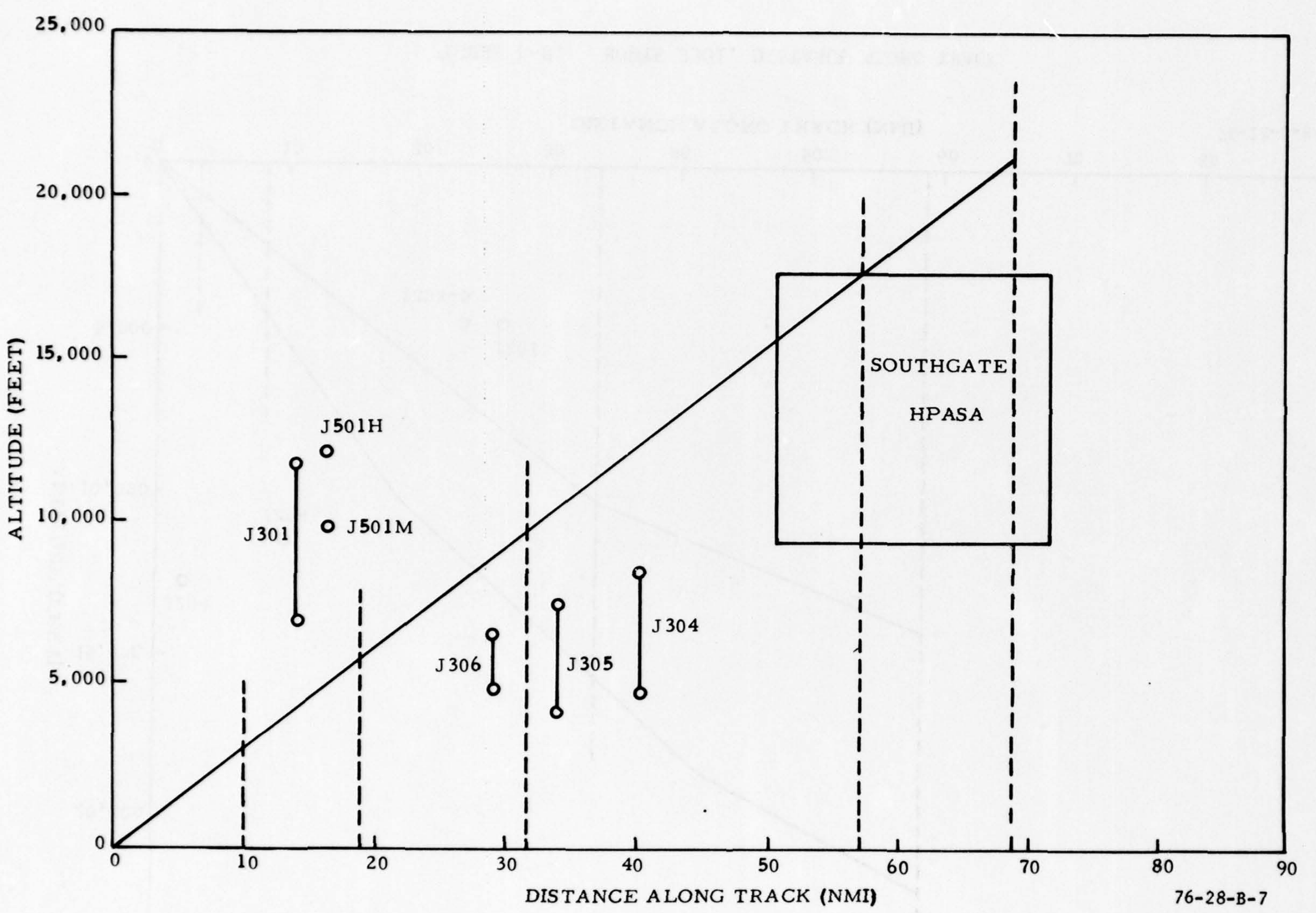


FIGURE B-7. ROUTE J205, DISTANCE ALONG TRACK

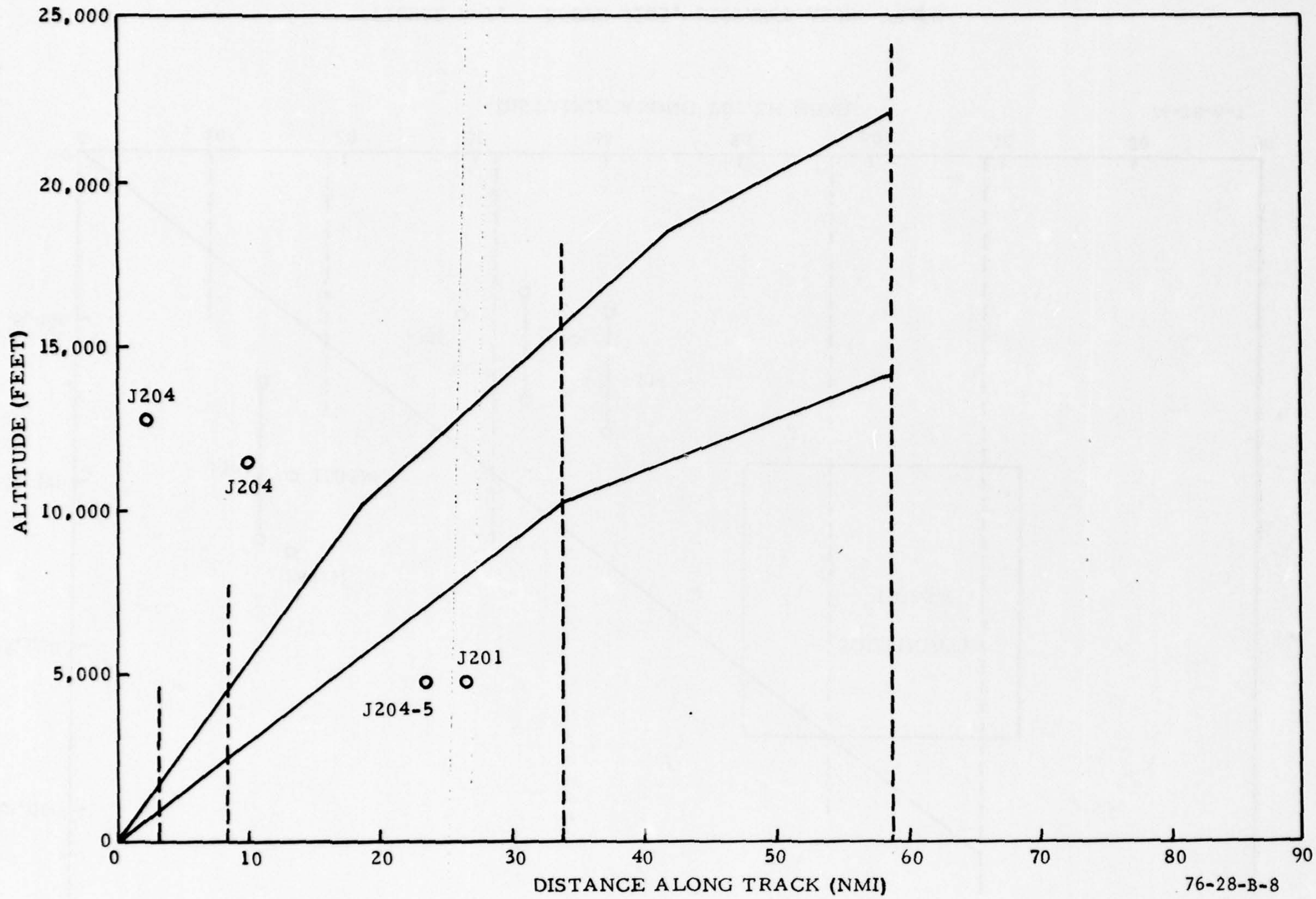


FIGURE B-8. ROUTE J301, DISTANCE ALONG TRACK

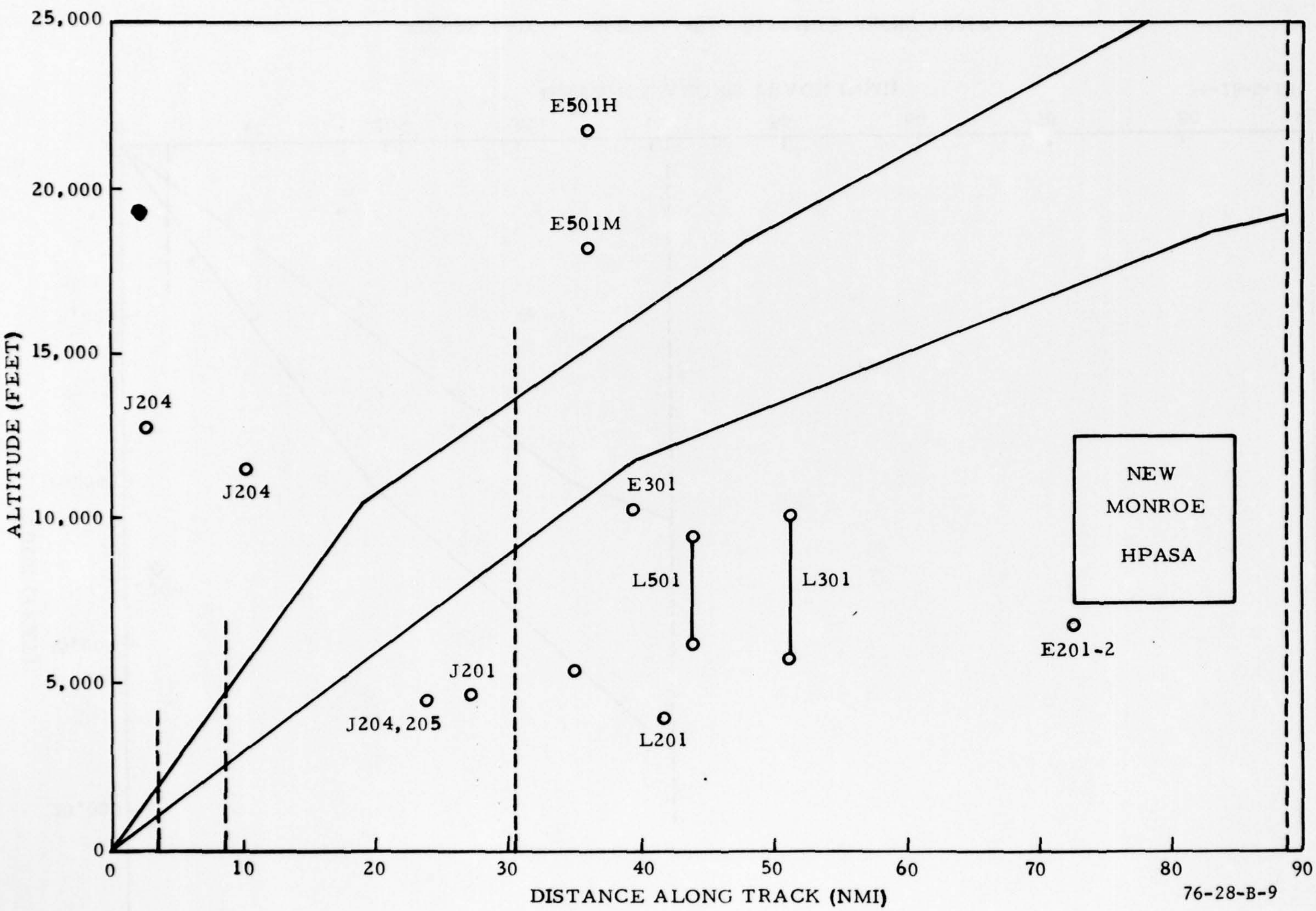


FIGURE B-9. ROUTE J302, DISTANCE ALONG TRACK

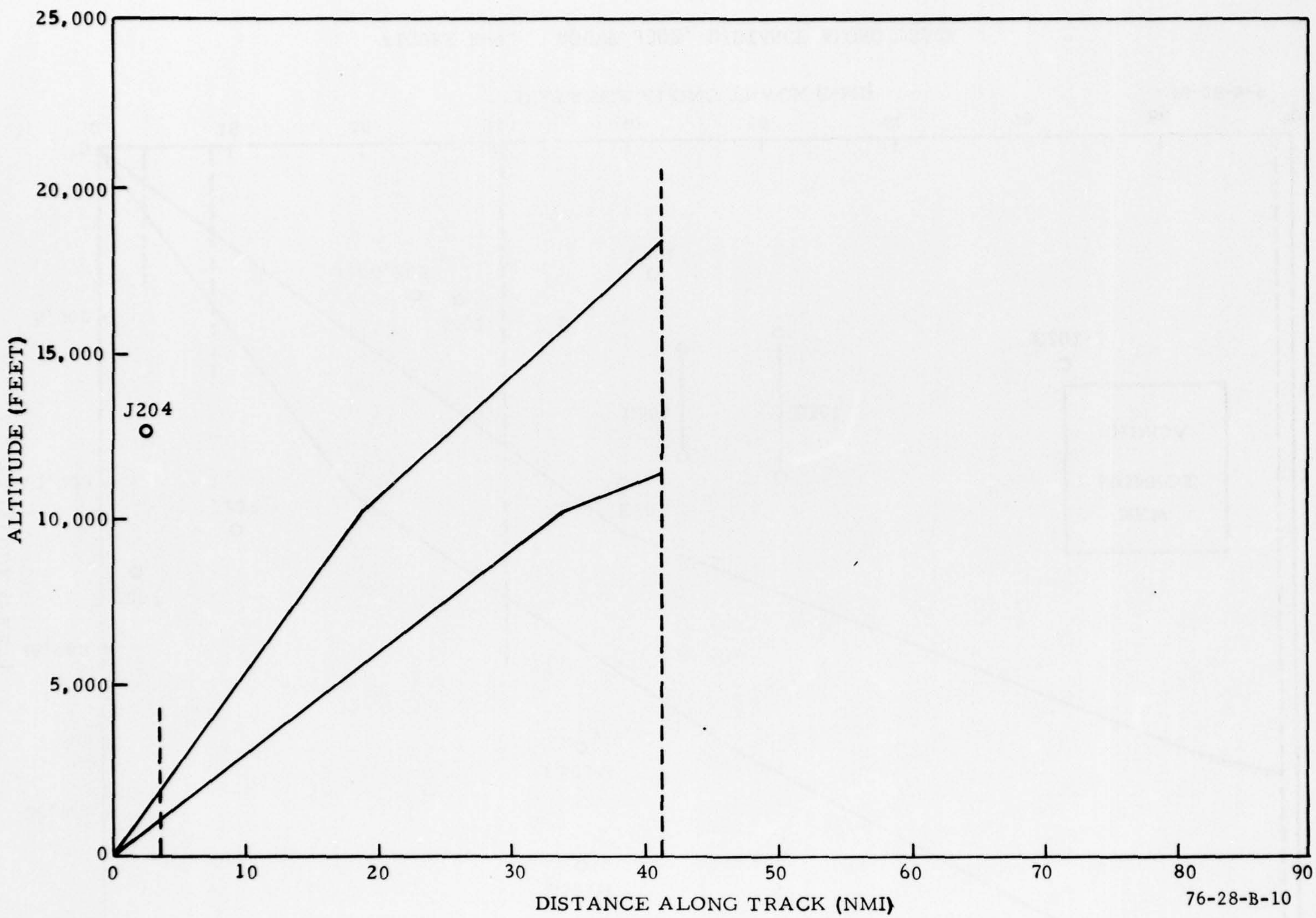


FIGURE B-10. ROUTE J303, DISTANCE ALONG TRACK

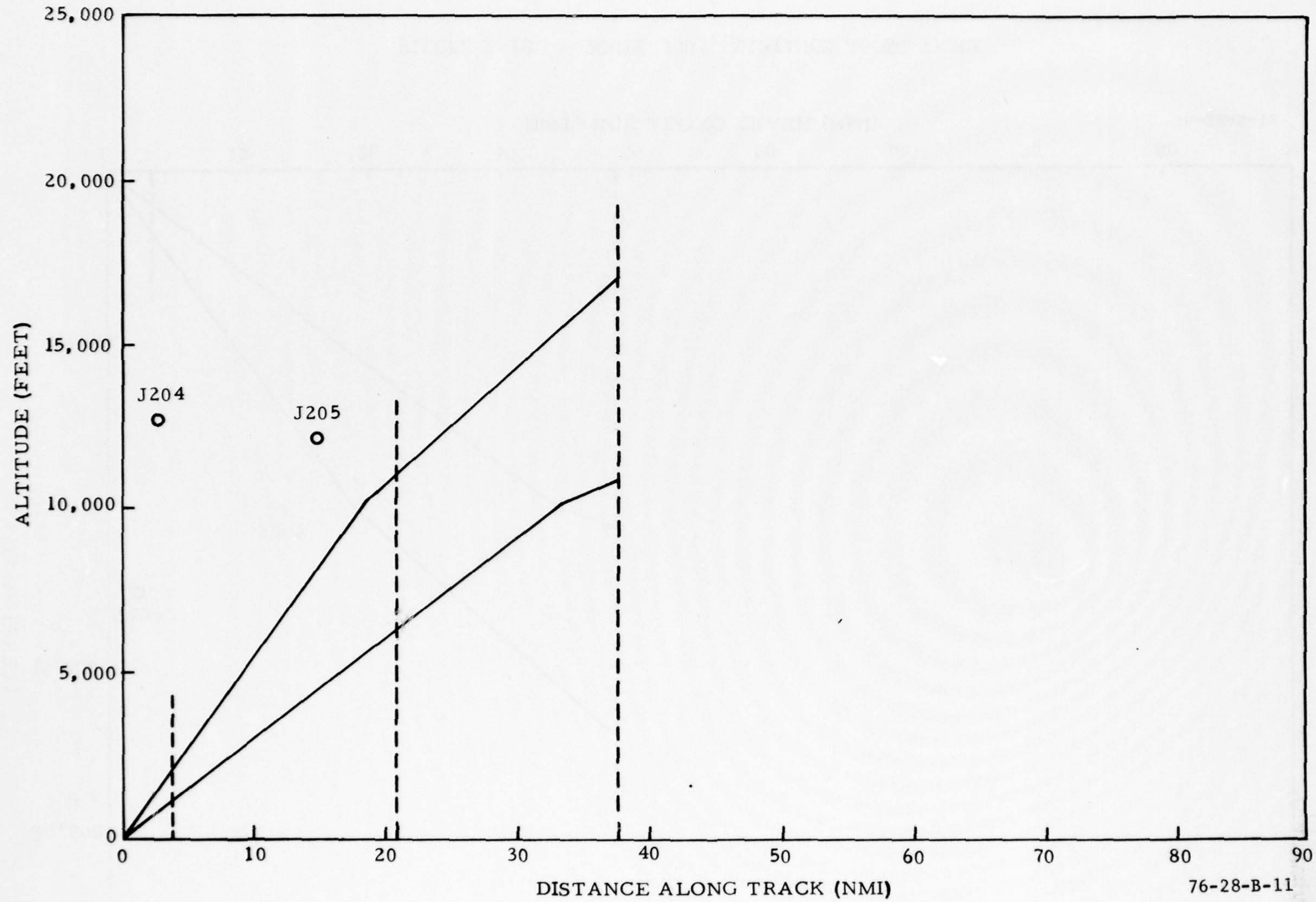


FIGURE B-11. ROUTE J304, DISTANCE ALONG TRACK

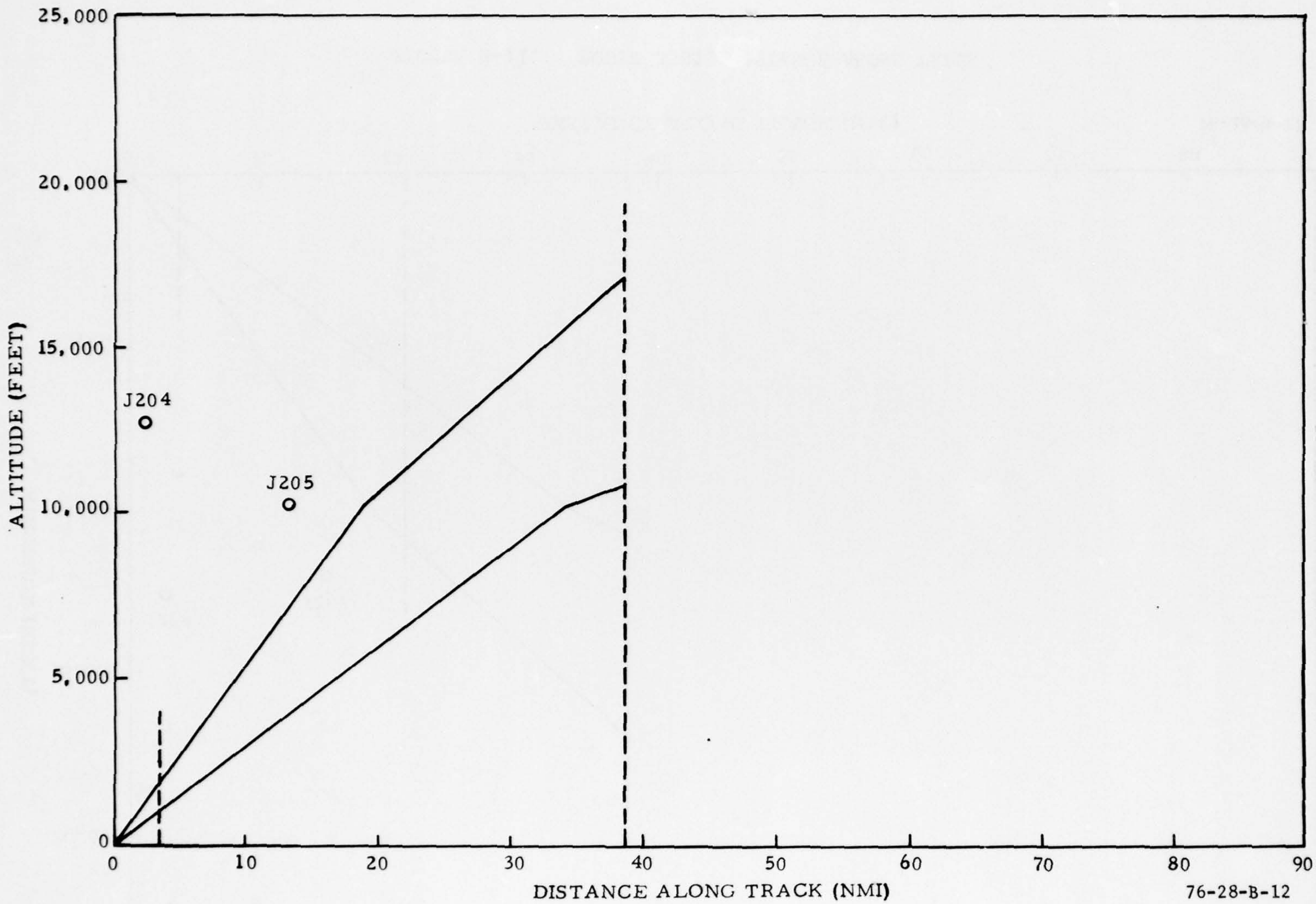


FIGURE B-12. ROUTE J305, DISTANCE ALONG TRACK

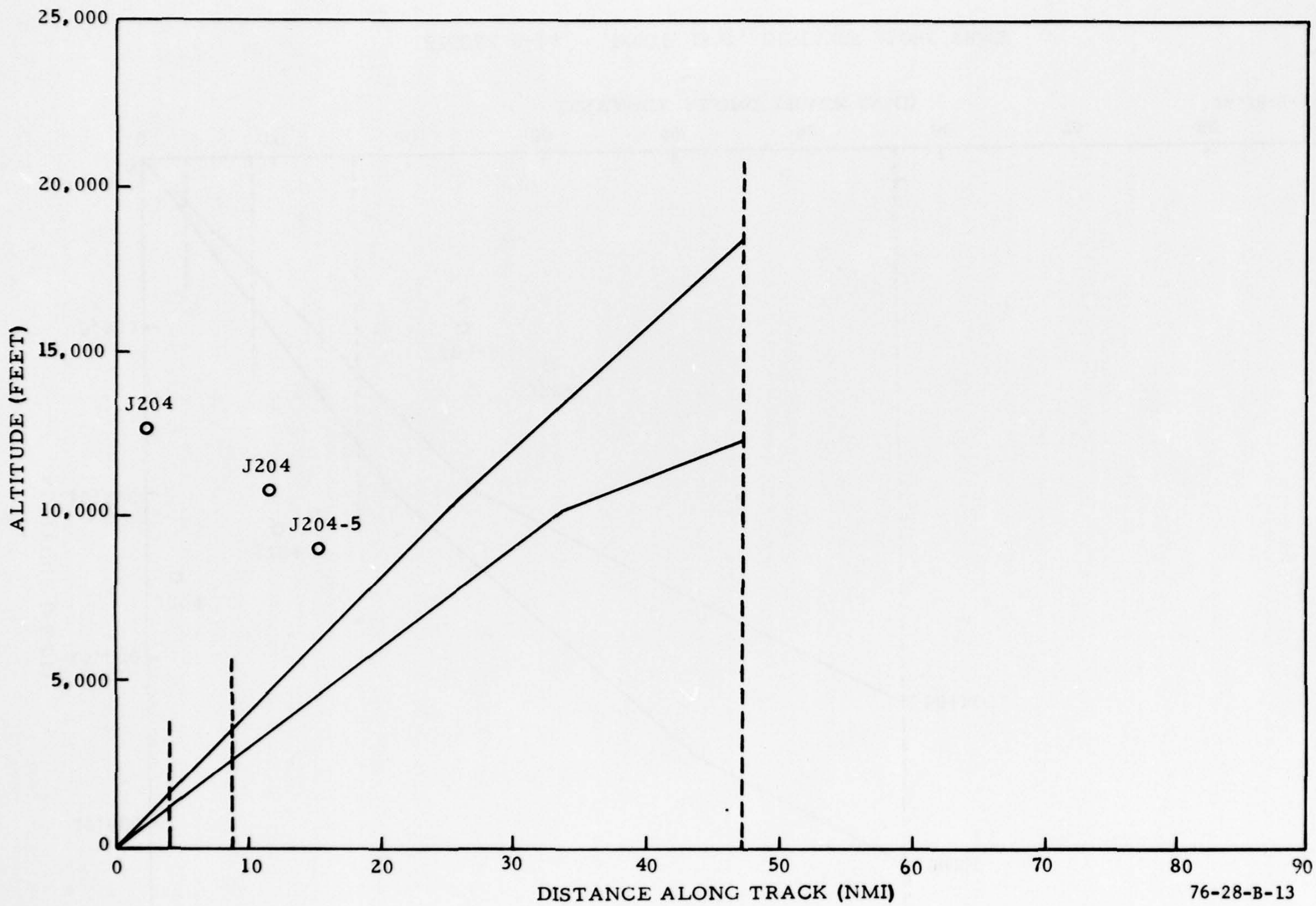


FIGURE B-13. ROUTE J306, DISTANCE ALONG TRACK

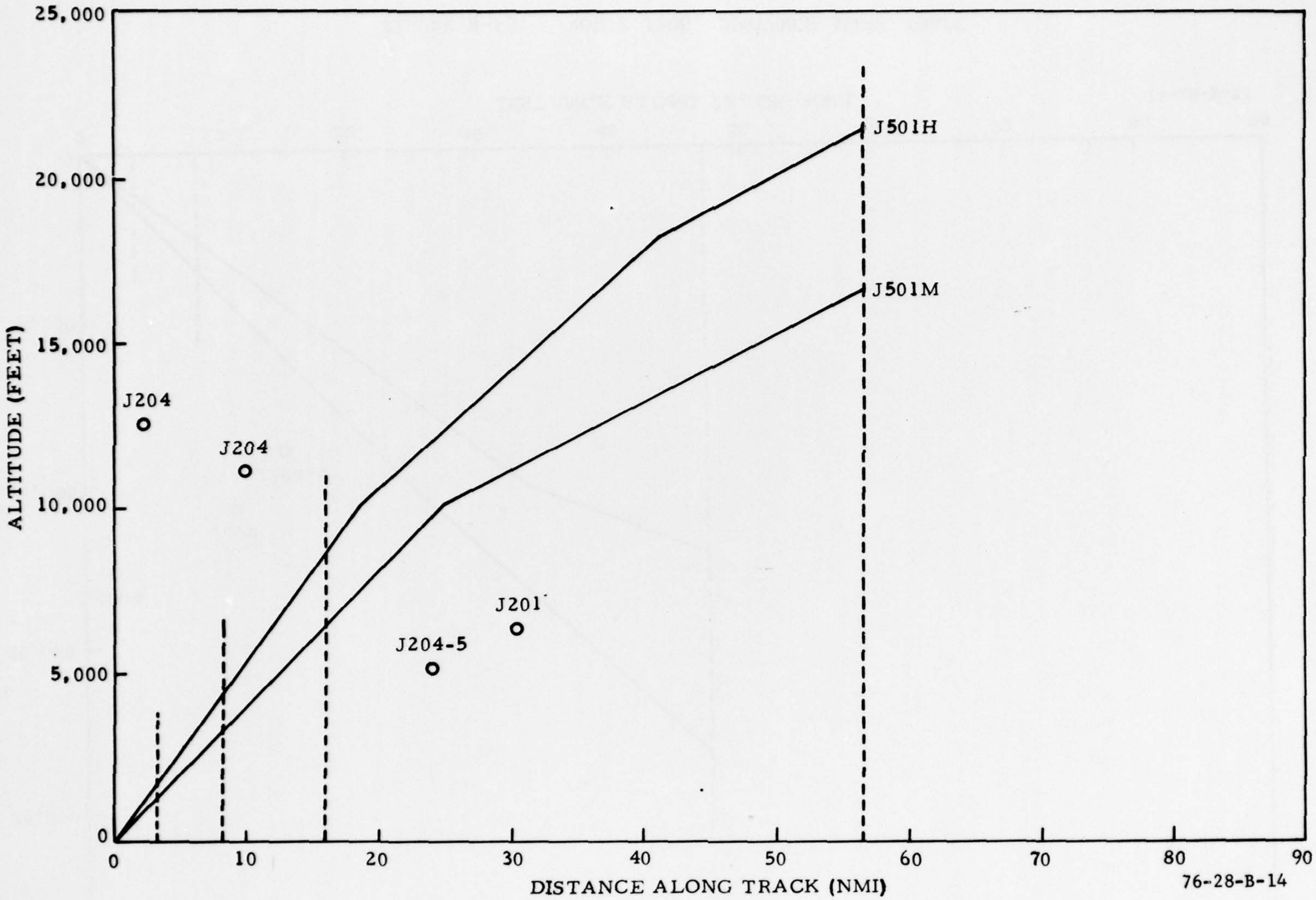


FIGURE B-14. ROUTE J501, DISTANCE ALONG TRACK

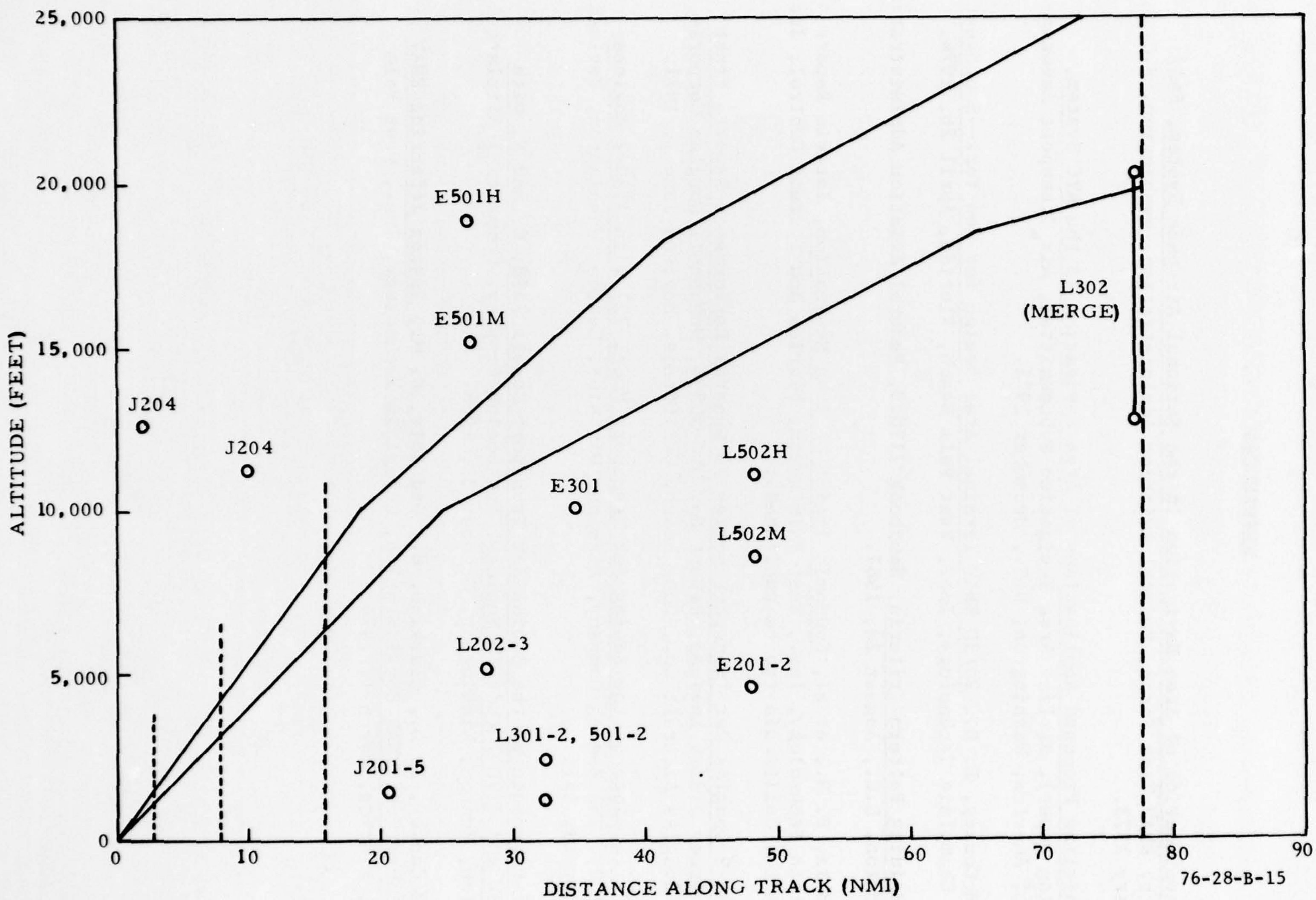


FIGURE B-15. ROUTE J502, DISTANCE ALONG TRACK

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APPENDIX C

FIELD CONTROLLER APPRAISAL OF THE USE OF RNAV/VNAV IN TERMINAL AREA ATC OPERATIONS

INTRODUCTION

Considerable interest has been expressed by various user groups in the involvement of current journeymen air traffic controllers, drawn from field facilities, for this simulation in which RNAV/VNAV operations are introduced into a high-density, terminal ATC environment. The purpose of the introduction of field controllers in the training, exploratory, and data collection phases of the simulation was to serve four major purposes: (1) to draw upon their current field experience in the refinement of the environment/procedures to be simulated, (2) to solicit their comments and reactions to the use of RNAV/VNAV in terminal area operations, (3) to derive quantitative simulation results from data collection runs in which they participated as test subjects, and (4) to provide them with some degree of familiarity with RNAV/VNAV operations through simulation.

Through the cooperation of the Air Traffic Service, Washington, D.C., and the various regions and facilities, five ATCS's were detailed to NAFEC to participate in the simulation. The presentation of their appraisal, independent of any comments or opinion expressed by the NAFEC pool controllers, is provided to be responsive to this interest.

The following apprisal was prepared by; D. B. Carlson, Atlanta Tower; J. M. Rosenthal, New York Common IFR Room; G. R. Frost, Jr., Bradley Tower; Ken Anderson, Minneapolis Tower; and K. A. Williams, Houston Tower.

TERMINAL AREA RNAV ROUTE STRUCTURE DESIGN (2D).

It is our opinion that the RNAV (2D) structure design originally planned for simulation required some modification to provide a higher degree of flexibility for the contrcller, if such modifications did not adversely impact on routes flown, altitude restrictions, etc., to an undue extent on the system user. A modified design was developed which appeared to satisfy this requirement. The major difference between this design, which was developed during the exploratory period for use in data collection runs and the original design, was in the area immediately to the east of JFK. The original design located the departure routes serving departures to the northwest, north, and northeast parallel to and inside the downwind leg. The new design, which is discussed in more detail in the attached report, placed the departure routes outside the downwind leg. This change appeared to have no adverse impact on the system user. The modification was made based on the following operational considerations:

1. There was a need for radar vectoring airspace so that we could compare a 100-percent radar-vectored operation with a 100-percent RNAV/VNAV operation. We would have been unable to compare these operations if we had to vector aircraft along the RNAV track.

2. The original design was made by Champlain Technology, Inc., and there were no provisions made for radar-vectored aircraft in their design.

3. The arrival route was moved inside the departures to give us more flexibility. We wanted to have the ability to shortcut traffic to runway 22L, from the downwind leg. This gave the final controller a true dump zone.

4. The new design had more waypoints. Two of the new waypoints were positioned closer to the outer marker. This enabled the final controller to switch any arrival to either runway by the use of RNAV.

TERMINAL AREA VNAV ROUTE STRUCTURE DESIGN (3D).

The original design planned for simulation allowed for the use of "stacked routes" for arrival/departure traffic. (The term "stacked routes" is used here to describe two or more routes having common or near-common horizontal paths which are separated vertically based on VNAV (3D) separation criteria.) It was envisioned that a unique application of VNAV arrival routes would result through the use of two-segment approaches which were to be included in certain parts of the simulation tests. However, when it was learned that the FAA did not support the use of two-segment approaches, this application was no longer considered viable. Therefore, a renewed and major emphasis was placed on determination of other potential uses for VNAV and its unique capabilities as they might relate to both terminal airspace design and ATC operational use of VNAV as a control tool.

In order to clarify the unique use of VNAV in combination with the two-segment approach concept, and why this combination appeared to offer some potential advantage in the use of stacked routes, figure C-1 is provided. As shown, using a two-segment approach to runway 22R and a single-segment approach to runway 22L, traffic from the east could fly stacked routes with the aircraft on the higher route intercepting the localizer for runway 22R at a higher altitude and executing a two-segment approach. The aircraft on the lower stacked route would intercept the localizer for runway 22L at a lower altitude, and vertical separation could be provided between the two aircraft until both were established on their respective localizers. Since two-segment approaches were dropped from the simulation tests, it is not known whether this combination would provide any operational advantage or not. However, two-segment approaches, when used as illustrated, did appear to provide a means for "unstacking" stacked routes.

Our effort to develop discrete VNAV routes was not limited to stacked routes, but was an extension of the previous work done by Champlain Technology, Inc., in their terminal route design activities and other analysis by SRDS and NAFEC prior to and during simulation planning. While the capabilities of VNAV were recognized by us as potentially beneficial to the ATC system user, it was

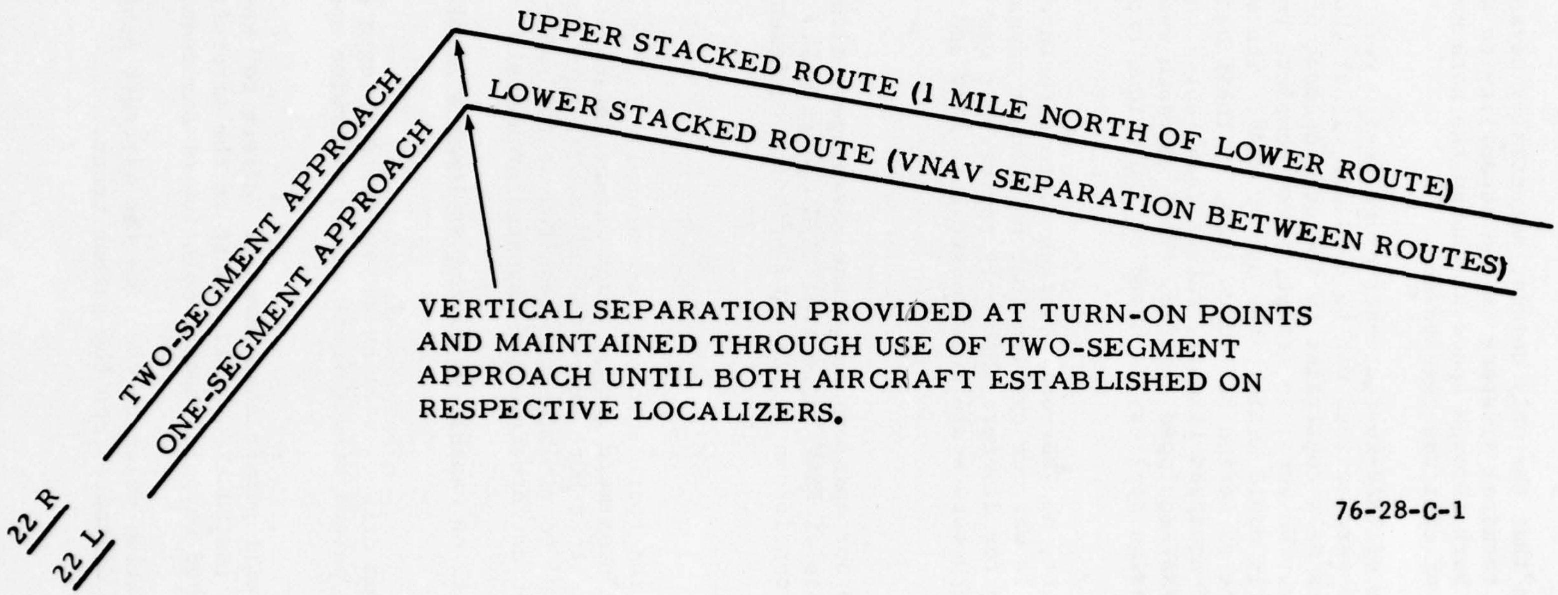

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FIGURE C-1. POSSIBLE UNIQUE APPLICATION OF VNAV TO THE TERMINAL AIRSPACE SYSTEM

the consensus of opinion that the only unique, potentially advantageous property of VNAV related to terminal airspace is the capability to define the vertical dimension of a path through space as though the path were described with an infinite number of altitude checkpoints.

A number of applications of VNAV-to-route-structure design were considered. During these studies, we were advised not to consider either the original or modified route structures as a constraint to the developement of routes discrete to VNAV operations. We were, in effect, given complete freedom to invent any route that potentially would exploit the use of VNAV. The effort was aimed at defining a route or series of routes that, by their nature, could be used exclusively by VNAV-equipped flights, rather than routes that could be used by both RNAV- and VNAV-equipped traffic. This approach was taken to identify any airspace design application based on the unique capabilities of VNAV.

As a result of this effort, no VNAV-only charted route structure or individual routes were developed. It was our opinion that no need or advantage could be found in airspace design for discrete VNAV-only routes. It was concluded that a good terminal route structure would accommodate both RNAV and VNAV traffic.

RNAV ATC APPLICATION.

The following represents our opinions as to the advantages, disadvantages, and limitations to the use of RNAV in terminal ATC operations. These opinions presuppose that certain conditions relative to avionics equipment and pilot performance are met.

CONDITIONS.

1. RNAV turn anticipation (both automatic and manual) will be performed in such a manner that the approximate ground track can be anticipated by the controller. This assumes that both automatic and manual turn anticipation procedures be standardized to minimize the requirement for radar vectoring to compensate for turns that deviate from the expected groundpath.

2. All RNAV flights will be capable of flying at least a 10-mile parallel offset.

3. All turns to and from offsets will be accomplished using a common departure angle from the parent/offset route unless otherwise specified by the controller.

4. All RNAV equipment will permit assignment of "direct to" waypoint clearances and compliance with such instructions will result in the aircraft flying a direct path to the assigned waypoint upon completion of any required turn.

5. Offsets may be cancelled prior to the time the aircraft achieves the assigned parallel offset distance from the parent track.

6. Flights on a "direct to" clearance can be assigned an offset parallel to the direct flightpath.

7. All RNAV functions simulated will be available.

8. Charted SID's and STAR's with altitude restrictions will be published and such SID's and STAR's will be so designed as to provide flexibility for spacing and sequencing of traffic equivalent to that required in a radar vector operational environment.

While condition 6 was not met by the DSF targets, condition 6 is believed to be realistic and available in some, if not all, RNAV systems, and our appraisal of the use of RNAV in terminal operations assumes that all of the preceding conditions would be met. This appraisal, based on both experience in the NAFEC simulation and in current field facility terminal air traffic control, is organized by specific areas of potential ATC impact and summarized in a general appraisal statement.

CONTROLLER RADIO COMMUNICATIONS. We feel that there would be some reduction in radio communications for the feeder controllers in a 100-percent RNAV/VNAV operation.

There would be a greater reduction of radio communications in a 100-percent RNAV/VNAV departure operation. However, there was minor reduction on the final control positions.

The reason for the reduced communications is that each SID departure or STAR arrival has a predetermined route to fly with all the altitude restrictions on it. The controller need only monitor the flight and make occasional RNAV maneuvers to accommodate overtaking or merging traffic situations.

THE ROLE OF RNAV MANEUVERS VS. PHASE OF FLIGHT. RNAV limitations: because of differences in navigational error and turn anticipation, separation standards in critical areas such as base leg or turns to final can and do diminish separation to less than prescribed minqums. Whereas radar vectors, being more precise when employed properly, can be benefically substituted in these same areas to provide exact required separation.

IMPACT OF MIXES OF RNAV/NON-RNAV OPERATIONS. Both the departure and feeder controllers found no appreciable differences between mixed traffic situations. It was just as easy to assign a heading off a fix or off the runway, as it was to issue an RNAV maneuver. However, the final controller's workload increases if he incorporates RNAV instructions for the RNAV aircraft and vectors to the non-RNAV aircraft.

IMPACT OF MIXES OF VNAV/RNAV OPERATIONS. No differences noted.

SYSTEM CAPACITY. RNAV will not affect traffic capacity in the terminal area, in that it is possible to run a 3-nmi final approach with RNAV or with radar vectors. The bottleneck required by present-day standards prescribes 3-nmi separation, and this can be accomplished with or without RNAV.

GENERAL APPRAISAL STATEMENT. It is our opinion that RNAV/VNAV procedures may well be applied in the terminal area to provide a safe, orderly, and expeditious flow of air traffic. We feel that RNAV routes, with altitude restrictions to which VNAV usage can be applied as pilots may desire, should be established at as many busy terminal areas as may be deemed beneficial by FAA and user groups. We feel that these routes should intially coexist with established airspace allocations to the extent possible to insure little or no adverse impact on present-day operations. We also feel strongly that radar vector procedures should be employed at the discretion of the controller in critical areas where RNAV/VNAV may not be as precise as radar. We believe that RNAV/VNAV will be beneficial to the user in that properly established routes can and will reduce flying miles and time. It will be beneficial to the user and more particularly to the controller under all traffic densities, in that the controller will normally have to provide fewer control instructions, subsequently allowing him to perform duties which may include handling more aircraft per sector, combining sectors or portions of sectors, and freeing him to provide both essential and additional services at a reasonable level.

It is felt that RNAV/VNAV could work well in a high-density terminal area. RNAV STAR's should be made for the entire route of flight including the final approach. RNAV/VNAV could be used to set up straight-in approaches to satellite airports that have no navigational aids.

VNAV ATC APPLICATION.

The following represents our opinions as to the advantages, disadvantages and limitations to the use of VNAV in terminal operations.

During the pre-data-collection and data collection periods of the simulation, little or no operational use was made of the functions peculiar to VNAV. While those functions common to both RNAV and VNAV were used to a major degree, there were no occasions found for the use of VNAV as a control tool. In addition, it is our opinion that while VNAV capabilities have the potential for providing advantages to the user in the manner in which climbs and descents can be accomplished, these potential advantages do not require the establishment of exclusively VNAV routes. Such advantages are available in a well structured RNAV terminal route system.

When VNAV vertical separation is being applied between aircraft on crossing courses, vertical separation criteria are predicated upon mathematical curves, which increase separation requirements proportionately with any change of the course angle convergence or divergence, and any increase of degree of vertical path angle. These RNAV separation standards can only increase the present-day minimums which dictate 1,000 feet vertical separation between IFR aircraft and which can more efficiently and effectively be applied through step-up or step-down procedures in use today. Also, due to the complex nature of the mathematical curve, a controller could very rarely move an aircraft laterally from an established track and still insure separation from a crossing course. Impromptu courses would be out of the question, as altitude separation requirements could not possibly be computed by the controller.

When VNAV vertical separation is being applied between aircraft in a parallel climb or descent on the same lateral track, separation criteria, in accordance with the vertical separation requirements curves, are increased over criteria which can be applied through the use of today's step-up or step-down procedures. If an aircraft is moved laterally from the main track, separation from another aircraft, which had previously been separated by the minimum criteria, either above or below, immediately ceases to exist due to the proportionate vertical separation increase caused by course angle divergence in the mathematical curve. Impromptu courses would again be out of the question, as controllers could not compute descent angles or altitude separation requirements.

RNAV could be used as a useful tool to pilots as a more economical means of climb or descent.

RNAV/VNAV could be used to set up straight-in approaches to satellite airports that have no navigational aids. It could also be used to set up an artificial glidepath to aid in VOR approaches, which would possibly lower minimums.